THE GEORGES BANK PETROLEUM STUDY

Volume II

Impact on New England Environmental Quality
of Hypothetical Regional Petroleum
Developments

by

Offshore Oil Task Group
Massachusetts Institute of Technology

Report No. MITSG 73-5
Index No. 73-305-Nme

Foreword

This is the second volume of a three-volume study of the impact on New England of a range of possible changes in the region's petroleum production, crude processing and products distribution system including a spectrum of hypothetical petroleum discoveries on the Georges Bank. Volume I focusses on the impact of these changes on regional income, Volume II concentrates on the impact on regional environmental quality and a third summary volume combines and summarizes the results. We emphasize that neither Volume I nor Volume II can be read independently of the other and in particular much of the analysis of Volume II depends on the results of Chapters 1 and 6 of Volume I.

This study was made possible through the encouragement and support of the National Sea Grant Program, the New England Regional Commission and the New England River Basins Commission. More complete acknowledgements will be found in the preface to the Summary.

The entire study and Volume II in particular was a joint effort for which the Offshore Oil Task Group is collectively responsible. However, Chapters II.1, II.2 and II.3 are largely the work of Mr. Robert Stewart and Professor David Hoult, Chapters II.4 and II.5 were the direct responsibility of Professor Stephen Moore and Mr. Robert Dwyer, and the analysis in Chapters II.6 and II.7 was done by Mr. Manuel Alvarez under the supervision of Professor James Fay.

Table of Contents

Chapter II.1
Oil Spill Probabilities

II.1.1 Introduction

The purpose of this volume is to investigate the environmental implications of the various developments hypothesized in Volume I, which implications are defined to be the changes in water and air quality effected by opting for one development hypothesis rather than another and the presently identifiable effects these changes will have on the biota. Many of these effects are imperfectly reflected, if at all, by the market process. Further, the result of these analyses will serve as input to the estimates of the impact on regional income of the effluents associated with the hypotheses.

These effluents fall into two broad categories: discharges, which we will define to be planned emissions from normally functioning equipment, and spills, which we take to be accidental emissions associated with the failure of some element of the system. The first three chapters of this volume concern themselves with oil spills into water.

The prime characteristic of a spill rather than a discharge is that it is probabilistic in nature. We can't be sure when or how often a spill will occur or how much will be spilled. The only means of handling this uncertainty is through probabilities.

The probability of an event, such as "exactly one spill over 42,000 gallons in 1978," is our odds on this event's occurring expressed on a scale of 0 to 1, 0 indicating that we're certain the event will not occur and 1 meaning that we're sure the event will occur, and the numbers in between expressing our relative likelihood that it will occur. In addition to events, we will often be dealing with numbers whose actual value we can't be sure of, such as "total number of oil spills over 42,000 gallons which will occur in New England in 1978" under a particular development hypothesis. Let's assume this number could be 0 or 1 or 2 or 3, and so on up to 100. In dealing with such random variables, we will attempt to assign a probability to each particular outcome. For example, the probability of 0 such spills might be estimated to be .4, the probability of 1 at .3, the probability of 2 at .2, and the probabilities of 3 through 100 at .0011 each. Such an assignment is known as probability distribution. It's an assessment of odds to all the possible outcomes. Often in dealing with random numbers to which we've assigned probability distributions, we will compute the average or mean of this number by simply multiplying each value by its probability (relative frequency). Thus, the mean of the above random number would be $0 \cdot .4 + 1 \cdot .3 + 2 \cdot .2 + 3 \cdot .0011 + 4 \cdot .0011 + \ldots + 100 \cdot .0011 = .755$.

There are several things to notice about the mean from this example. For one thing, it is not necessarily true that the random variable will, with high probability, equal the mean. In this case, we are quite certain there will not be .755 spills in a year. It is impossible. It is not even true that the actual value of the random variable will necessarily be near the mean. In the example, the actual number of spills can be 100, which is many times the mean.

The mean becomes considerably more meaningful as one deals with larger and larger samples. For example, if one were to observe the number of such spills that took place in 20 successive years and divided this total by the number of years, then the result, the "average" over this period, will with high probability be close to the mean. This probability will increase with the number of years sampled. Thus, for a long-run or large-sample phenomenon, the mean of distribution can be quite interesting.

We will be dealing with two types of mean in the rest of this chapter:

1) The mean amount spilled in a particular time period by a particular element of a hypothesized development as above.

2) The mean time between spills of certain size categories emanating from a particular element of a hypothesized development plan. Four spill size categories will be considered:

   i) All spills

   ii) Spills greater than 42,000 gallons (large spills)

   iii) Spills greater than 300,000 gallons (very large spills)

   iv) Spills greater than 3,000,000 gallons (extremely large spills)

This second type of mean will allow us to address the likelihood of the low probability but extremely important large spills, which is not really addressed by the first type of mean. Once again, however, the fact that we estimate that the mean time between spills over 300,000 gallons emanating from offshore towers is, say, 4 years does not imply that one such spill will occur every 4 years. Two such spills could occur a month apart or 10 years apart. It merely implies, rather, that over a long period of time, the average number of spills per year will with high probability be close to 1 over 4. The inverse of the mean time between spills is the mean number of spills per year, which we will call the mean spill incidence.

II.1.2 Assumptions required to obtain estimates of mean volume spilled and mean spill incidence as a function of regional petroleum activity

The last section pointed out that even if we knew the mean of the amount spilled or time between spills, we would still not know exactly how much or how often. The problem is further complicated by the fact that we can't be sure just what the values of these various means are. We shall have to be satisfied with estimates of these means based on whatever data we can find which appears relevant. What we require is a procedure for obtaining from such data these estimated means for a particular development hypothesis,which procedure is sensitive to the amount and type of regional petroleum activity associated with this hypothesis.

A variety of approaches was considered. For example, one measure of the activity of tankers might be the number of port calls made by tankers. The mean number of regional tanker spills might be presumed to be proportional to this measure of activity. Similarly, the mean spillage incurred at a bulk storage and transfer facility might be considered to be proportional to the number of handling operations performed. The list can be as long as our knowledge of the operations permits. Moreover, since it is not clear that the spillage depends on just one variable, we might investigate multiple dependencies, such as relating spillage to the number of port calls and the density of shipping in the ports, and the narrowness of the channels. Unfortunately, this is all speculation, and short of an elaborate regression analysis, there is no way to choose between the possibilities, and defend the selection rigorously. We considered performing such an analysis, but upon examining the available data, we found the findings would very likely be inconclusive, and therefore that the study group's resources could be better employed elsewhere. We have chosen rather to:

a) break down each development hypothesis into the following elements: regional refinery, offshore platforms, offshore pipeline, regional bulk storage and transfer facilities and regional tanker and barge traffic;

b) obtain the amount of oil handled, in and out, within the region by each element from the results of Chapter I.2 as a function of time;

c) assume that the mean amount of oil spilled and the mean spill incidence in each element within the region is proportional to the volume of oil handled by the element within the region;

d) use existing data sources to estimate the mean amount spilled per barrel throughput and the mean spill incidence per barrel throughput by element. For those activities which handle the oil twice within the region, such as a products distribution system served by a regional refinery, the throughput is counted twice.

Step (c) is the key and there is really no strong justification for it other than that it is the most obvious starting point for analysis. However, many other assumptions are possible and this should be kept in mind in interpreting our results. It appears the Coast Guard data, particularly after a few years of data are available, is susceptible to some rather interesting statistical analyses testing the above and other assumptions.

II.1.3 Spill data

Essentially four sources of data were available to us concerning oil spills:

i) a rather comprehensive survey conducted by the Coast Guard for spills in U.S. waters in 1971;

ii) a tabulation of large spills worldwide prepared by the Geological Survey;

iii) a tabulation of tanker accidents worldwide in which spills were reported prepared by Westinform Ltd.;

iv) reports of individual ports on their spill experience, principally Milford Haven in Wales.

The Coast Guard began monitoring and logging oil spills in U.S. waters in the early part of 1970. The monitoring system became fully operational in late 1970. Through the offices of CDR Daniel Charter (Chief of the Environmental Coordination Branch, Marine Environmental Protection Division, U.S. Coast Guard Headquarters, Washington, DC) we obtained a copy of the 1971 spill reports in punched card form. The data contained information on the type of oil spilled (categorized by flammability grade); the source of the spill; the Coast Guard District and state in which the spill occurred; a generic description of the body of water; the date; the primary cause; and the quantity spilled. We grouped the data by source and region and used the results in determining the mean spillage figures. Unfortunately, some interesting information is not included in the reports. Particularly important from this standpoint is the omission of the name of the harbor, bay or river in which the spill occurred, and the weather conditions during the incident (only when the conditions appear to be directly responsible for the spill are they reported). Of less importance, but still handicapping, is the lack of agreement between the Coast Guard's oil categories and the Army Corps of Engineers commodity groupings (see next paragraph). This introduced an element of uncertainty in comparing the quantity handled with the quantity spilled. It is our hope that in the future the Coast Guard's reporting format will be expanded to include the Corps of Engineers codes for the port and commodity, and that an additional two- or three-digit code will be developed for the weather conditions (it might be possible to implement the Weather Bureau's codes directly). This would involve no more than ten or eleven new digits, and could be inserted in the present format with no change to the existing items.

Our procedure requires data not only on spillage but also on volumes handled by system elements. For tankers and barges we used the Corps of Engineers' data relating to waterborne commerce. Chapter I.2 analysis indicates this data may be somewhat inaccurate and perhaps incomplete. Nevertheless it is by far the most comprehensive summary of waterborne commerce in the U.S. The summary for 1970 (Waterborne Commerce of the U.S.) was used to determine the volume of petroleum transported in the New England region. This data consists of two separate summaries. One part breaks out barge and ship traffic in a harbor or canal on the basis of number of trips and draft. This portion relates to the Corps channel maintenance activities. The second portion lists the total volume of goods brought into any given port, or shipped through an inland waterway. Several thousand commodities are listed, and the port listing seems very complete. The breakout of petroleum products also seems very complete, individual categories ranging from crude to tar to naphtha. In all some 15 petroleum commodities are included.

Data on the total production of crude oil and gas from the outer continental shelf is available from the Geological Survey in a publication entitled Outer Continental Shelf Statistics. It appeared to be very complete and is probably quite accurate, since royalty payments are based on these figures. It was the source of all our production figures used analyzing the spillage from offshore towers.

Refinery production figures were taken from the "Oil and Gas Journal"'s Crude Oil Pipeline Atlas. The reason for selecting this rather unusual summary was that it allowed us to determine which refineries were located on a waterway. This was necessary, because the Coast Guard spill data related only to these refineries. The production figures and the completeness of the listing were then checked against the 1972 National Petroleum News Fact Book Issue (Mid-May, 1972, McGraw Hill) with the result that no major discrepancies were found. If we should have listed some refineries erroneously, the result would (probably) be an overestimate of the number of refineries on the water and subsequently an underestimate of the predicted spillage from refineries. The error is probably small, however, and it is certainly much less than the errors induced by our blanket assumption that mean spillage is proportional to the throughput, and only the throughput.

The throughput of the large offshore pipelines was taken to be equal to the total crude production from the Federal OCS in the Gulf of Mexico. Barges are used to transport a very small portion of the crude ashore from these towers.

II.1.4 Summary of 1971 Coast Guard spill data

Figure II.1.1 summarizes the 1971 spill data. The breakout of industry-related sources excludes tanker and tank barge spills that occurred on a river. These spills were excluded because they are not typical of the spills we can expect in New England.

Several important things can be seen from this figure. First, 4,017 spills (or 54% of all the oil spills) occurred at industry-related sources. Secondly, these spills account for 73% of all the oil spilled in the U.S. as reported to the Coast Guard (these percentages might be higher if river spills were included). Finally, we can see that in terms of the total volume spilled the "terminal" (5.295 million gallons) and the "pipeline" (898,000 gallons) categories account for 6.192 million gallons or about 98% of all the oil spilled from industry sources. Spills from tankers and tank barges offshore (outside restricted waters) are of negligible significance in the data.

In general, the Coast Guard feels they are catching almost all the sizable spills. Very rarely do they discover a spill to which they cannot assign a source. However, the one category for which this is least true is undoubtedly offshore ship traffic. Thus, the results for this category have to be viewed with some caution. However, it does appear clear that ships are much less likely to get into trouble at sea than near the terminals.

Figures II.1.2 and II.1.3 breakout the terminal and pipeline spills. Figure II.1.2 indicates that tankers and tank barges account for about half the terminal spillage, and the principal causes here are groundings and collisions. The refineries appear to be the next most important group, but an investigation of the incidents comprising the refinery data indicated that over 90% of all the oil spilled came from one incident. This phenomenon is not unexpected in a statistical sense. Spills will be of almost any size, from very small to immense, although

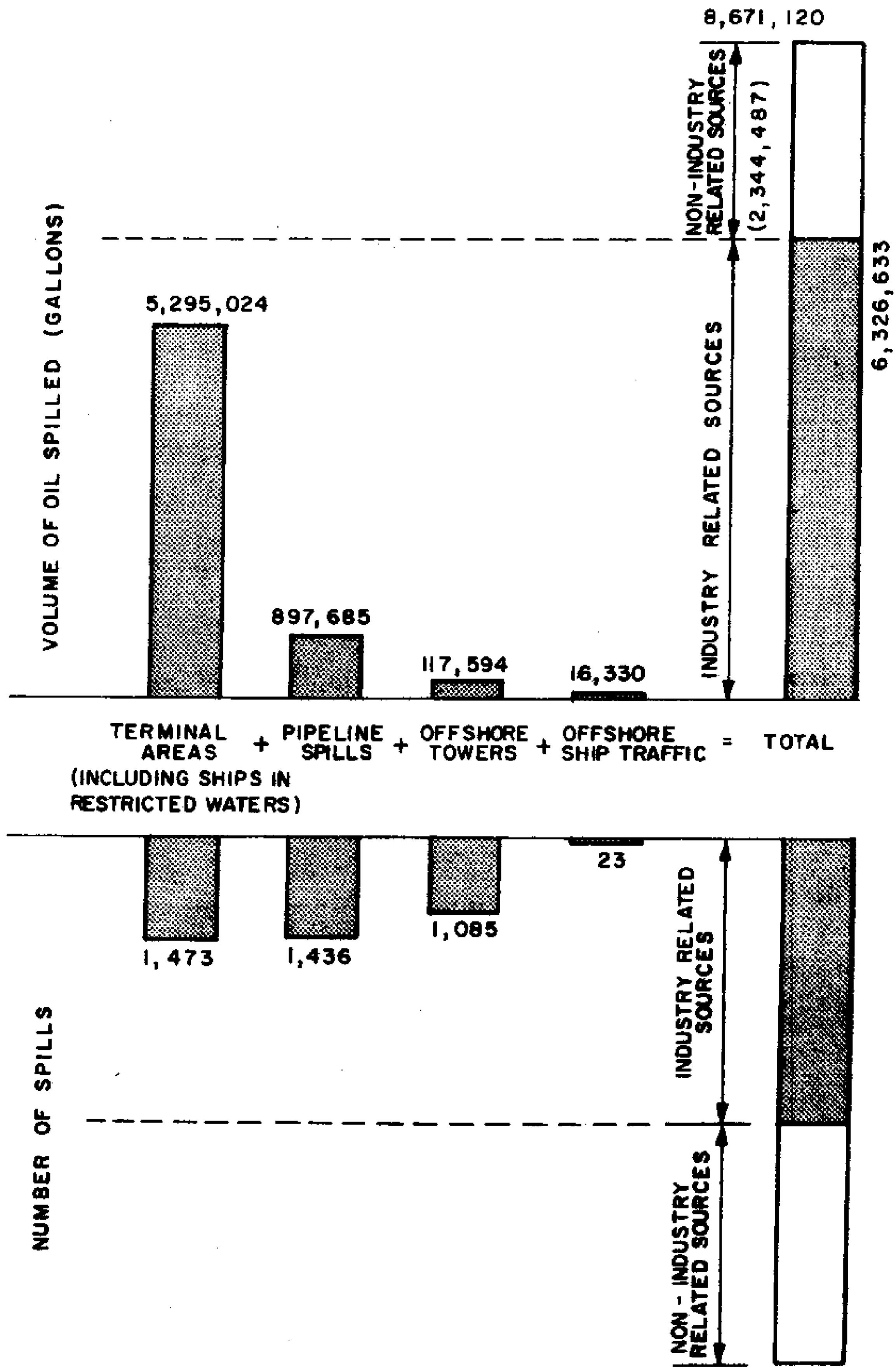


FIGURE II-1-1 SUMMARY OF OIL SPILLS OCCURRING IN THE U.S. IN 1971

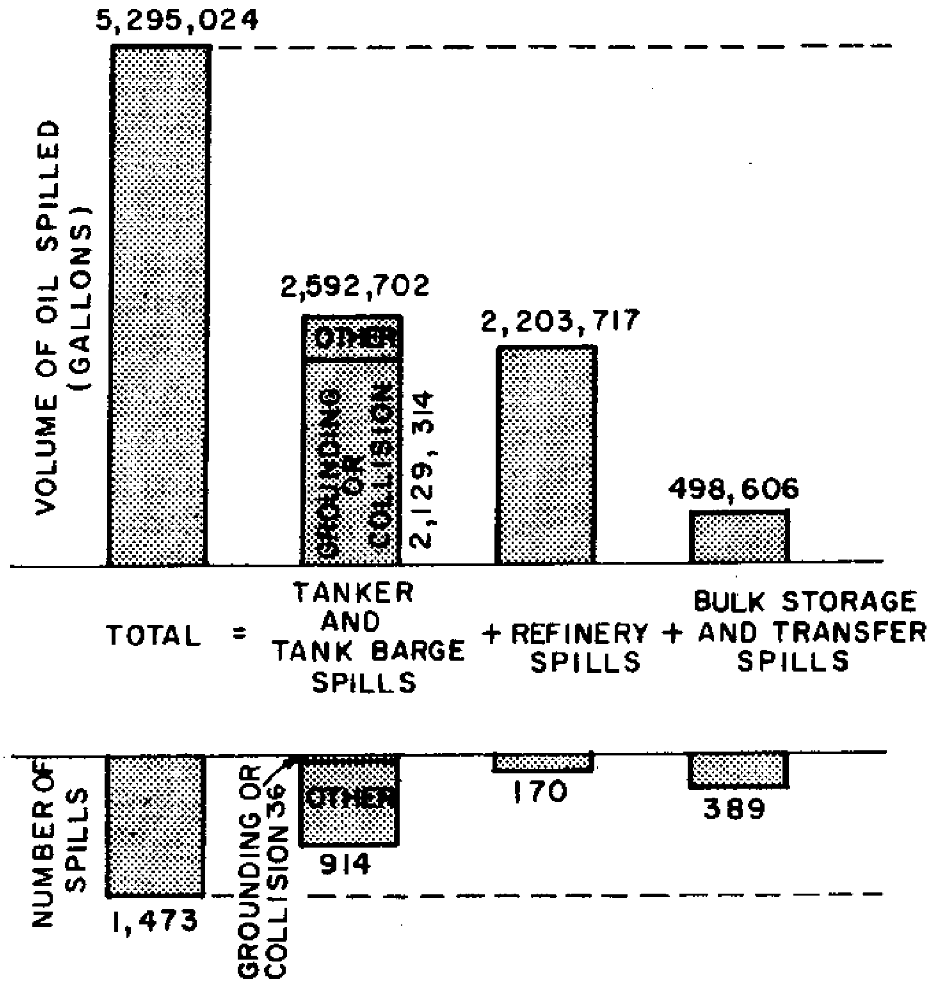


FIGURE II-1-2 SUMMARY OF TERMINAL AREA SPILLS FROM INDUSTRY RELATED SOURCES

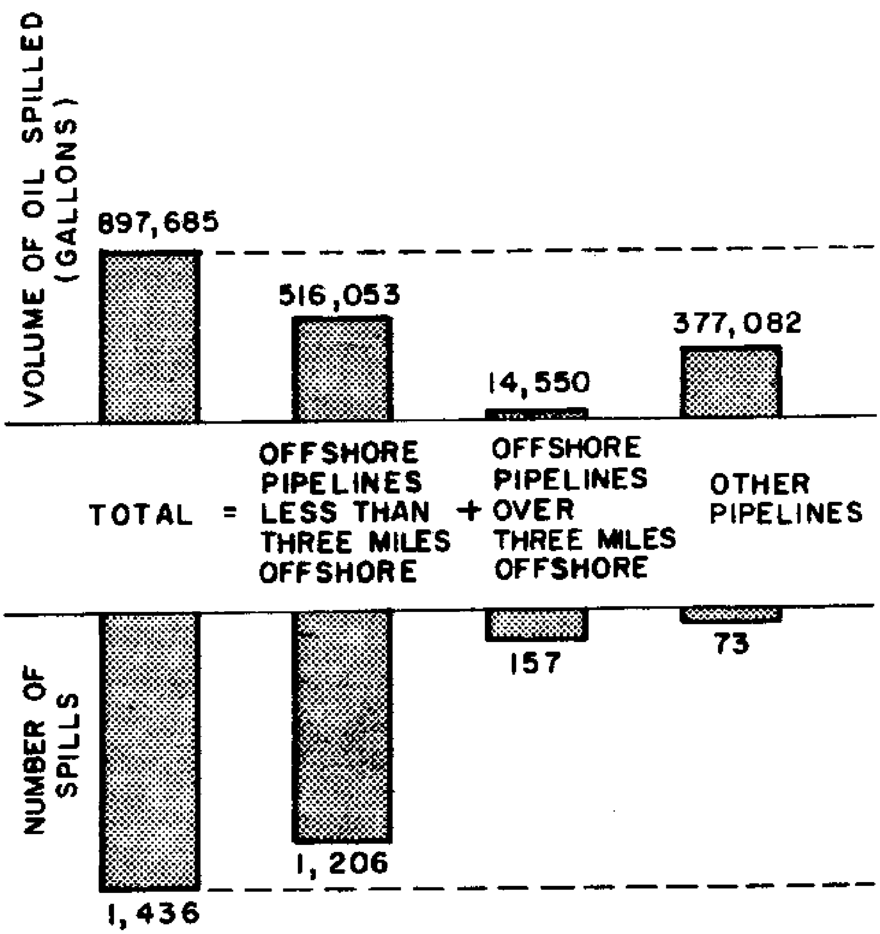


FIGURE II-1-3 PIPELINE SPILLS FROM INDUSTRY RELATED SOURCES large spills will be rare. This implies that a very large sample will be required to properly represent this probability distribution. In this specific instance, 170 samples is probably a factor of ten too small to assure a good estimate of the mean spillage. As a consequence, single unlikely event, a 2,000,000 gallon spill, can assume an overwhelming importance in the data. If we overlook this one large spill then we can see that the refineries and the transfer and storage categories are quite similar.

Figure II.1.3 details the pipeline spillage. It can be seen that in the Coast Guard data, the vast majority of pipeline spills are due to releases from offshore pipelines. These offshore pipelines almost without exception serve to transport crude oil from offshore towers. There are, however, two or perhaps three distinguishable classes of pipeline. The oldest pipelines will lie nearshore and they will service the nearshore towers. In general, they will be small-diameter pipes and they could be as old as the first wells put into production in the Gulf of Mexico (about 1949). Further offshore, there exist gathering networks which serve to bring the production from various platforms to one central point. These pipes are also of a small diameter, but they are newer, since the development of the more distant fields wasn't begun until the late fifties. Finally, there are the large-diameter common carriers which serve to bring the production of the far offshore fields to shore. These pipelines are called common carriers, because they carry several companies' oil ashore.

It is the opinion of Coast Guard officers stationed in the Gulf that the old, nearshore pipelines are the principle polluters in the Gulf of Mexico. To check this, we broke the offshore pipeline data into a nearshore group (less than three miles from shore) and a group lying further offshore (over three miles). It was felt that this would help identify the culprit. As can be seen, the vast majority of the spillage occurred within three miles of shore. Consequently, we are fairly certain that the old, small pipelines are the principal source.

This finding has considerable bearing on the problem at hand, because any development on Georges Bank would utilize pipeline systems like those lying further offshore in the Gulf of Mexico. Therefore, for the 1971 data, our estimate of the spillage will be based on the smaller amount spilled over three miles offshore. There are, of course, holes in this argument, the principal one being that the nearshore spills are more likely to be observed and reported. They are also more likely to be investigated, thereby helping validate the quantity spilled. However, the Coast Guard has found that they rarely discover a tower spill that hasn't already been reported, even in their overflights of the more remote towers. We may presume pipeline spills are equally well monitored.

In reviewing Figures II.1.1 through II.1.3 the reader might feel somewhat uncomfortable with the quantities of oil spilled. It is a common preconception that the spills are in general much larger. This is probably due to the large amount of publicity given the major oil spills. In fact, this result bothered us, so we attempted to compare our 1971 results with the Coast Guard's 1970 results. We were somewhat disconcerted to find that the total volume of oil spilled in 1970 was about 15.25 million gallons versus our total volume of 8.7 million gallons. This disparity lead us to search out the historical data shown on Table II.1.1. The data is essentially paraphrased from a U.S. Geological Survey Report of about the same title. The spill incidents are broken out by source. Pipelines, refineries, offshore towers, and bulk storage and transfer facilities are included. Not included are tanker and tank barge spills because the Geological Survey information was not detailed enough to allow a determination of where the

Table II.1.1
Recorded Large Spills Involving Pipelines, Refineries, Bulk Storage and Transfer, 1957-1971, Spills > 42,000 gallons
(For tanker/barge spills see Table II.1.8)

Pipeline Spills:

Location	Cause	Reported Amount	Date
West Delta Area, LA, OCS	Anchor dragging	6,600,000	15.10.67
Persian Gulf	Break	4,000,000	20.4.70
Buckeye, Lima, OH	Unknown	690,000	14.1.69
Alabama	Rupture	590,000	10.12.70
Chevron, MP 299, LA, OCS	Unknown	310,000	11.2.69
Gulf, St. 131, LA, OCS	Anchor dragging	250,000	12.3.68
Michigan	Human error	210,000	7.10.71
Tennessee	Break	184,000	6.10.71
Louisiana	Unknown	155,000	17.3.71
Missouri	Human error	147,000	12.20.71
Texas	Rupture	140,000	6.12.71
Kansas	Rupture	118,000	18.10.71
Illinois	Break	108,000	23.7.71
Tennessee	Vandalism	100,000	26.12.71
North Dakota	Unknown	84,000	4.5.70
Wyoming	Break	84,000	3.3.69
Immigration Canyon, Utah	Rupture	84,000	7.9.69
Indiana	Leak	60,000	9.1.70
Virginia	Rupture	75,000	6.5.71
Illinois	Break	63,000	8.7.71
Indiana	Break	60,000	9.5.71
Mississippi	Break	55,000	5.3.71
Texas	Break	42,000	21.11.71
Pennsylvania	Break	42,000	28.11.71
Texas	Struck by bulldozer	42,000	23.6.71
New Mexico	Unknown	42,000	14.7.71

Refineries:

Moron, Venezuela	Dumped through sewer	678,000	29.3.68
Humbolt Bay, CA	Hose eruption	60,000	12.68

Bulk Storage and Transfer

Seawarren, NJ	Tank failure	8,400,000	11.69
Indiana	Tank collapse	3,500,000	23.11.70

---

*Source: U.S. Geological Survey, Conservation Division, "Recorded Oil Spill Incidents Involving 1,000 or More Barrels Since 1957", July 29, 1971, revisions Sept. 1, 1971, and Dec. 30, 1971

Table II.1.1 (continued)

Bulk Storage and Transfer (continued)

Location	Cause	Reported Amount	Date
Pennsylvania	Ruptured dike	3,000,000	13.11.70
Ohio	Rupture	2,600,000*	31.1.70
Connecticut	Human error	800,000	15.6.70
Puget Sound	Human error	230,000	26.4.71
Sears Oil Co., NY	Unknown	100,000	7.1.69
Massachusetts	Unknown	100,000	4.5.70
Kodiak Naval Station, Alaska	Overflow	80,000	4.4.70
Ohio	Unknown	80,000	27.9.71
Niagara River	Unknown	60,000	22.12.70
Connecticut	Human error	55,000	16.11.70
Texas	Failure	55,000	1.2.70
New York	Overflow	60,000	25.3.71
New York	Safety plug blow	45,000	4.6.71

Offshore Towers:

Location	Cause	Reported Amount	Date
Shell ST 26 "B", LA, OCS	Fire	2,200,000	1.12.70
Chevron MP 41 "C", LA, OCS	Fire	1,300,000	10.3.70
Union "A", Santa Barbara, CA	Blowout	420,000**	28.1.69
Signal SS 149 "B", LA, OCS	Hurricane	210,000	3.10.64
Continental EI 208 "A", LA, OCS	Collision	108,000	8.4.64
Mobil SS 72, LA, OCS	Storm shift	105,000	16.3.69
Tenneco SS 198 "A", LA, OCS	Hurricane	67,000	3.10.64

*This spill was reported in the Coast Guard data as 2,000,000 gallons.

**Presumably, this is initial discharge. Other observers place the total amount spilled at Santa Barbara at up to 3,250,000 gallons.

incident occurred (offshore or in restricted waters). Table II.1.1 indicates that, considering all the sources contained in the table (everything except tankers and tank barges) there have been only eight spills over one million gallons in a 14-year period. If we included all tanker and tank barge spills, this figure would still be only 23 spills, and this is for the whole world. Note also that of these eight large spills, five of them occurred in 1970. One of the five was not in the 1970 Coast Guard data (the Persian Gulf spill) and if we eliminate the remaining four then we have only 5.3 million gallons spilled in 1970. This fact makes two points. One is that the very large spills account for a large proportion of the total amount spilled. Thus, yearly totals can vary considerably. Two, 1970 appears to have been an unusually bad year for large spills.

II.1.5 Spill causality

As a first step in analyzing the Coast Guard data, we made an attempt to determine the type of cause of spill. We have broken the Coast Guard cause information into two groupings (see Table II.1.2). One group, which we have termed "chronic" spills, involves causes which are presumed to be attributable to operator indifference - causes which could be corrected by tighter supervision and management without any real changes in technology. The other category, labeled "accidental", involves serious failure of sizable system elements. The presumption is that attacking these causes will in general involve considerable investment and, perhaps, some major changes in technology.

The rationale behind this breakdown is that, if the majority of spillage were "chronic" in nature, then assuming tighter supervision and enforcement in the future, our results would tend to overestimate the amounts which will be spilled. If,on the other hand, the majority of spillage is due to "accidental" causes, then the data can be used directly under the assumption that present technology will continue to be used.

The results of this analysis are contained in Table II.1.3. Note that while the "chronic" spills make up about 70% of the total number of spills, they only account for 25% of the total volume spilled. In terms of average spill size, the chronic spill averages out at 580 gallons, whereas the accidental spill averages out at 4,100 gallons. Of course, there is a strong dependence on the source, and it appears that offshore towers and pipelines have a very high proportion of chronic spills. Based on this analysis, we cannot expect the terminal region spillage to get appreciably better through simple managerial innovations. However, it seems likely that some of the spillage from offshore towers and pipelines might be reduced through more stringent supervision.

Table II.1.2

Spill Causality Groupings

Chronic Spills	Accidental Spills
(Presumed to be attributable to operator indifference)	Collision
Other	Fire
Other rupture or leak	Explosion
Minor vehicle structural failure	Grounding
Other storage tank leak	Capsizing or overturning
Line leak, small	Sinking or floundering
Pipe leak, small	Well blowout
Corrosion or rust	Tank rupture
Defective fitting valves or closures	Major vehicle structural failure
Loose fitting valves or closures	Storage tank rupture
Other personnel failure	Hose rupture
Tank overflow, inadequate sounding	Line leak, large
Tank overflow, incorrect valve alignment	Pipe leak, large
Tank overflow, list in trim error	Weld failure
Tank overflow, failure to shut down when topped off	Other equipment failure
Tank overflow, topping off at excessive rate	Valve failure
Incorrect valve handling	Pump failure
Flanges not properly secured	Alarm failure
Improper hose connection	Automatic shutdown device failure
Over-pressurization of cargo tank	Sabotage
Other deliverate discharges	Vandalism
Pumping bilges	Other natural phenomena
Pumping ballast	Natural seepage
Disposal of other waste oil	Heavy unanticipated rain
Discharge under EPA permit	Flooding
Discharge under COE permit	Unanticipated freezing
Unknown causes	Unanticipated heavy winds
	Unanticipated heavy seas
	Unanticipated external heat

These conclusions are only as strong as our ability to categorize the causal factors, and there is a fair amount of room for speculation in our selections. Consequently, this data should be considered only from the standpoint of giving us some insight to the problem, and not as a reliable indicator of industry's behavior. In later sections, we will ignore the distinction between "accidental" and "chronic" spills. All spills will be treated as accidental. Based on the discussion above, we might expect our predictions to be overly pessimistic (conservative) on this basis, as some of the spillage, particularly that occurring from offshore towers and pipelines, may be avoided in the future through tighter supervision of operations.

Table II.1.3
Chronic and Accidental Spills
1971 U.S. Coast Guard Spill Reports

	Number of Spills		Volume Spilled (gallons)	
Source	Chronic	Accidental	Chronic	Accidental
Terminal Areas: Including refineries, bulk storage and transfer facilities and tankers and tank barges in restricted waters	975	498	850,000	4,450,000
Pipelines	1,206	230	628,000	270,000
Offshore Towers	650	435	73,000	44,000
Offshore Ship Traffic	19	4	11,000	5,000
Total	2,850	1,167	1,562,000	4,769,000

II.1.6 Regional breakdown of Coast Guard data

Figures II.1.4 through II.1.7 break out the 1971 data USCG on a regional basis. Figure II.1.4 summarizes the oil spilled in New England. In 1971, according to the Coast Guard, 850,000 gallons of oil were spilled in New England, of which 750,000 gallons emanated from petroleum industry sources.* Note that while no oil is produced in New England, and only a small quantity is refined, the New England area nevertheless now accounts for about 10% of all the oil spilled in the U.S. Of this 10% about 93% can be attributed to tankers and tank barges and bulk storage and transfer facilities. This high spillage is not completely unexpected since the New England region accounts for about 30% of the national consumption of distillate and residual fuel oil due to both its cold winters and its heavy dependence on oil rather than gas or coal. Also the region is unique in its complete dependence on small tankers and barges for secondary redistribution of products. Nevertheless, the regional spillage rate from tankers and barges is 50% higher than that on the Gulf and 10 times higher than that reported for the Middle Atlantic. We distrust the latter figure. However, as we shall see, the regional spillage is also a factor of ten higher than in certain well-managed foreign ports. Figure II.1.5 summarizes the Coast Guard data for the Mid-Atlantic region. Note that about one-half as much oil was reported spilled as in New England. The reported figure may be low due to several causes. There is a substantial portion of the region which falls under E.P.A. regulation, and spill incidents in these areas may not find their way into the Coast Guard data. Moreover, the condition of much of the water around New York City is so polluted and the public indifference so great that many spills might go unnoticed.

---

*Remember this does not include shoreside discharges such as crankcase oil disposal, unburned products of combustion, etc.

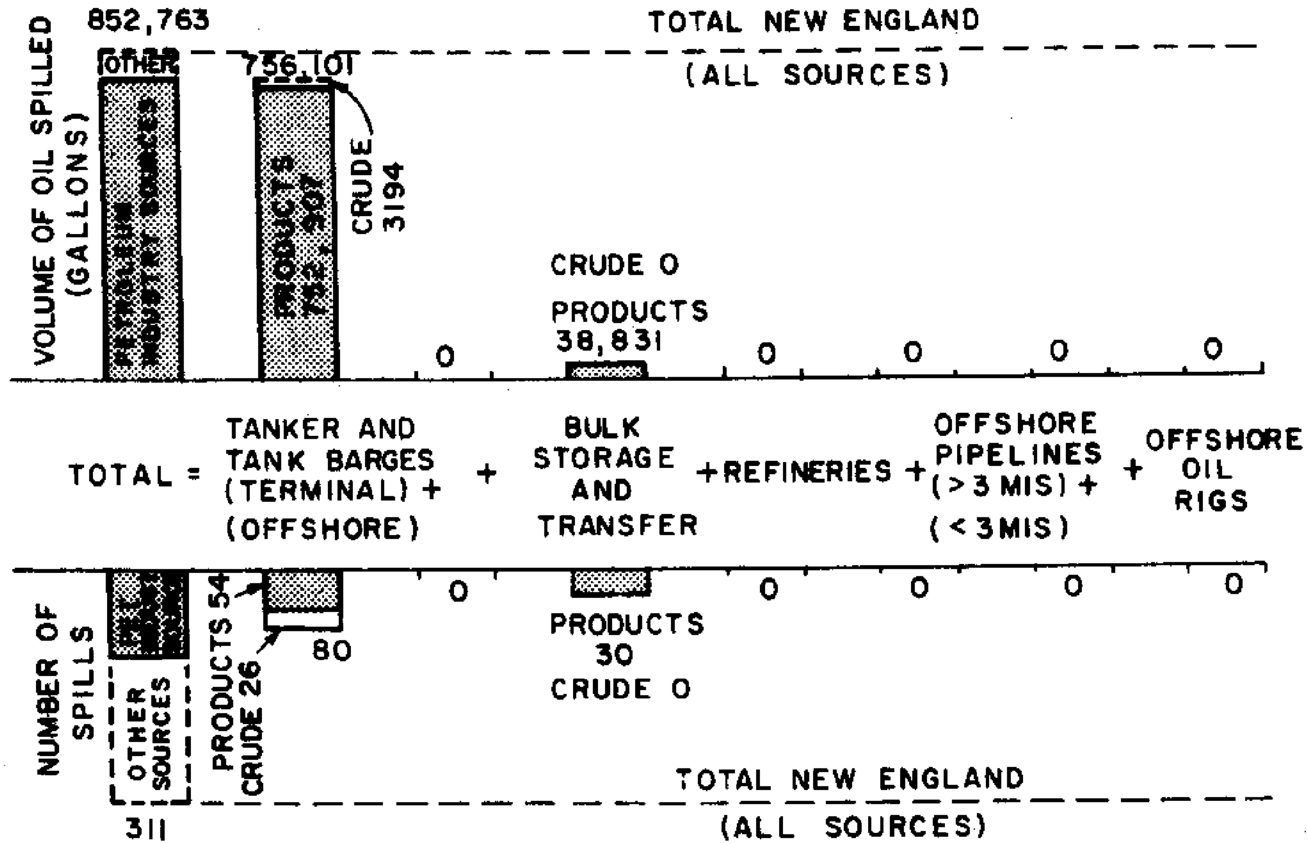


FIGURE II-1-4 REGIONAL SPILL STATISTICS FROM INDUSTRY RELATED SOURCES NEW ENGLAND

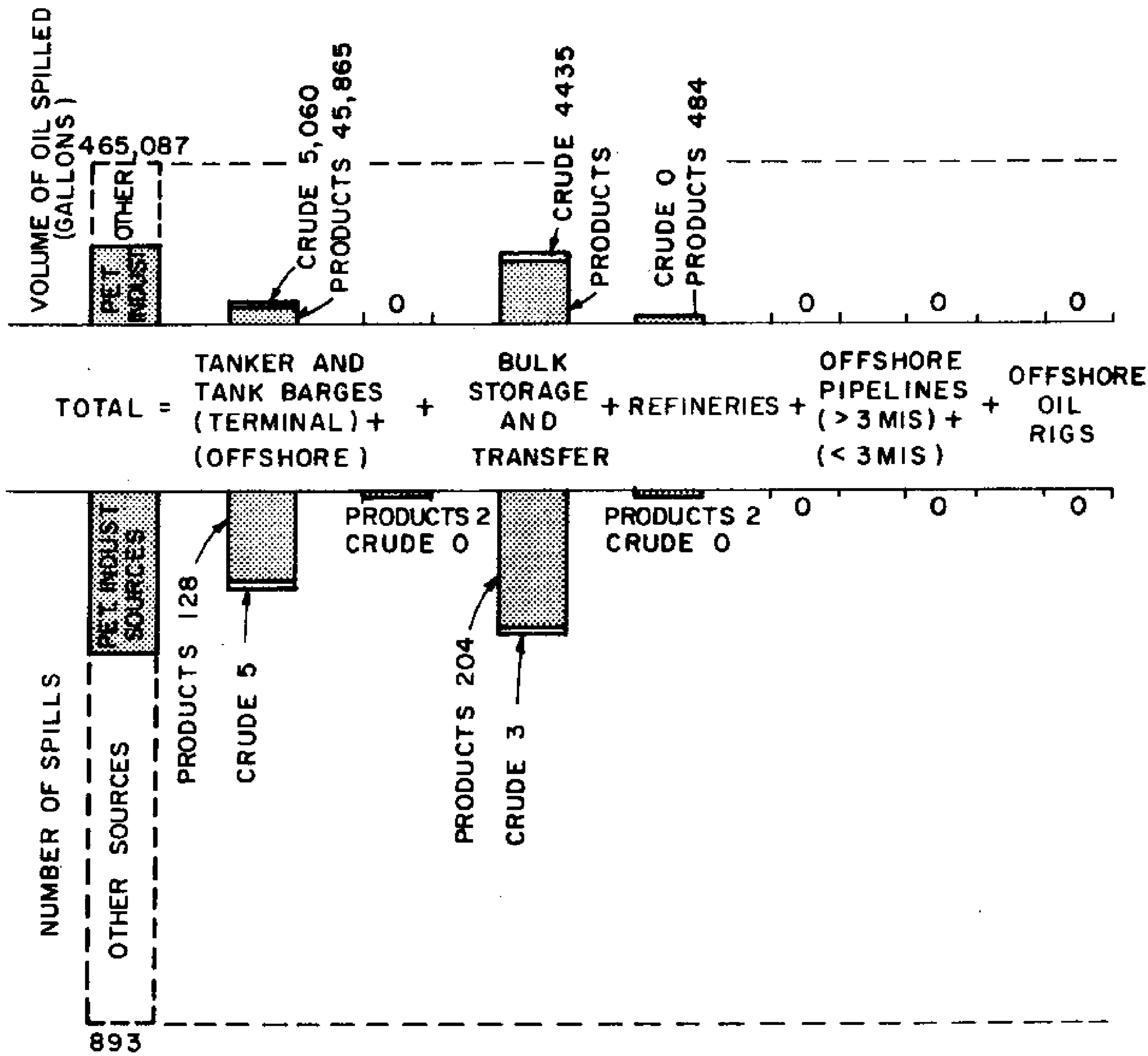


FIGURE II-1-5 REGIONAL SPILL STATISTICS FROM INDUSTRY RELATED SOURCES MID-ATLANTIC STATES

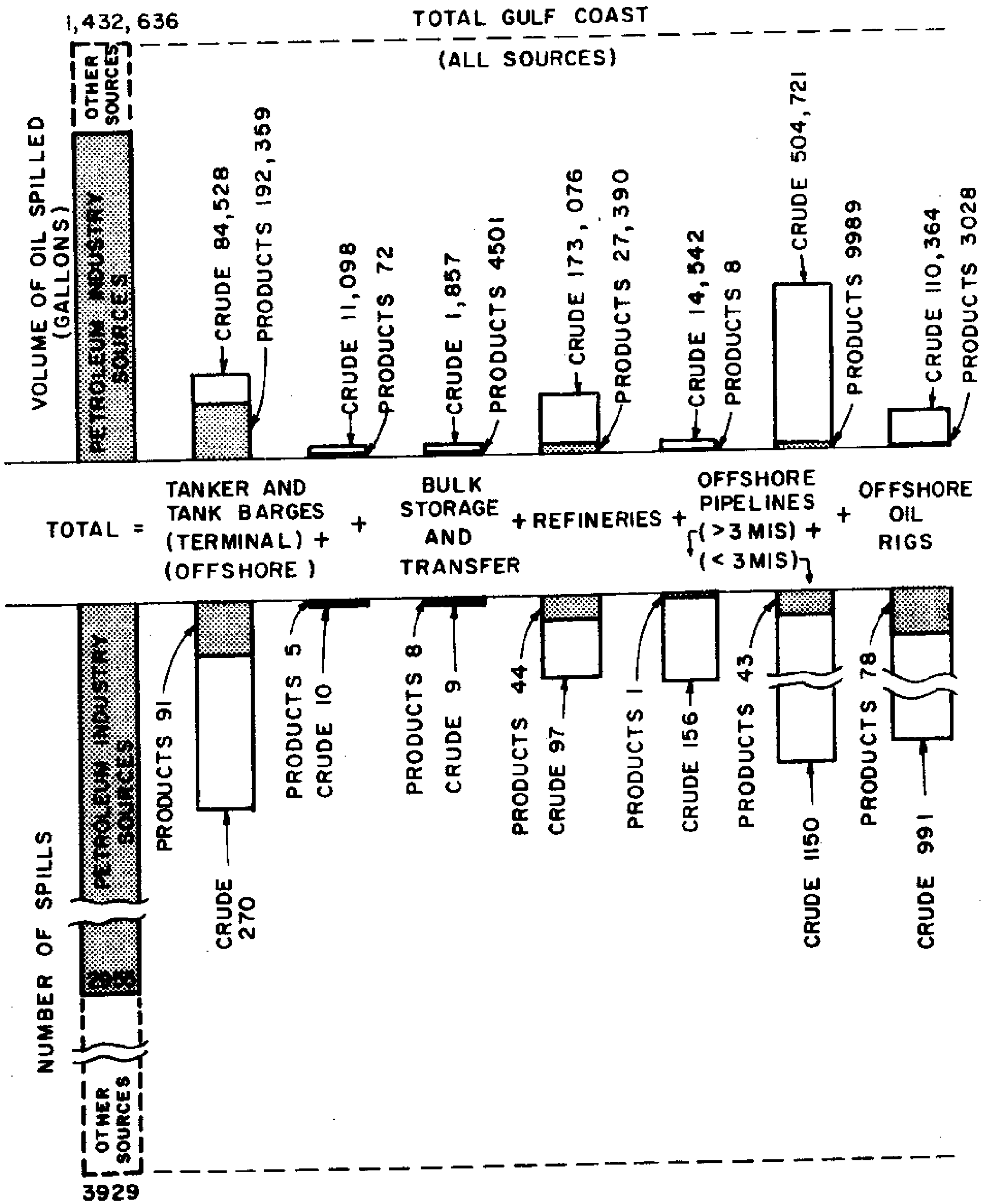


FIGURE II-1-6 REGIONAL SPILL STATISTICS FROM INDUSTRY RELATED SOURCES GULF COAST

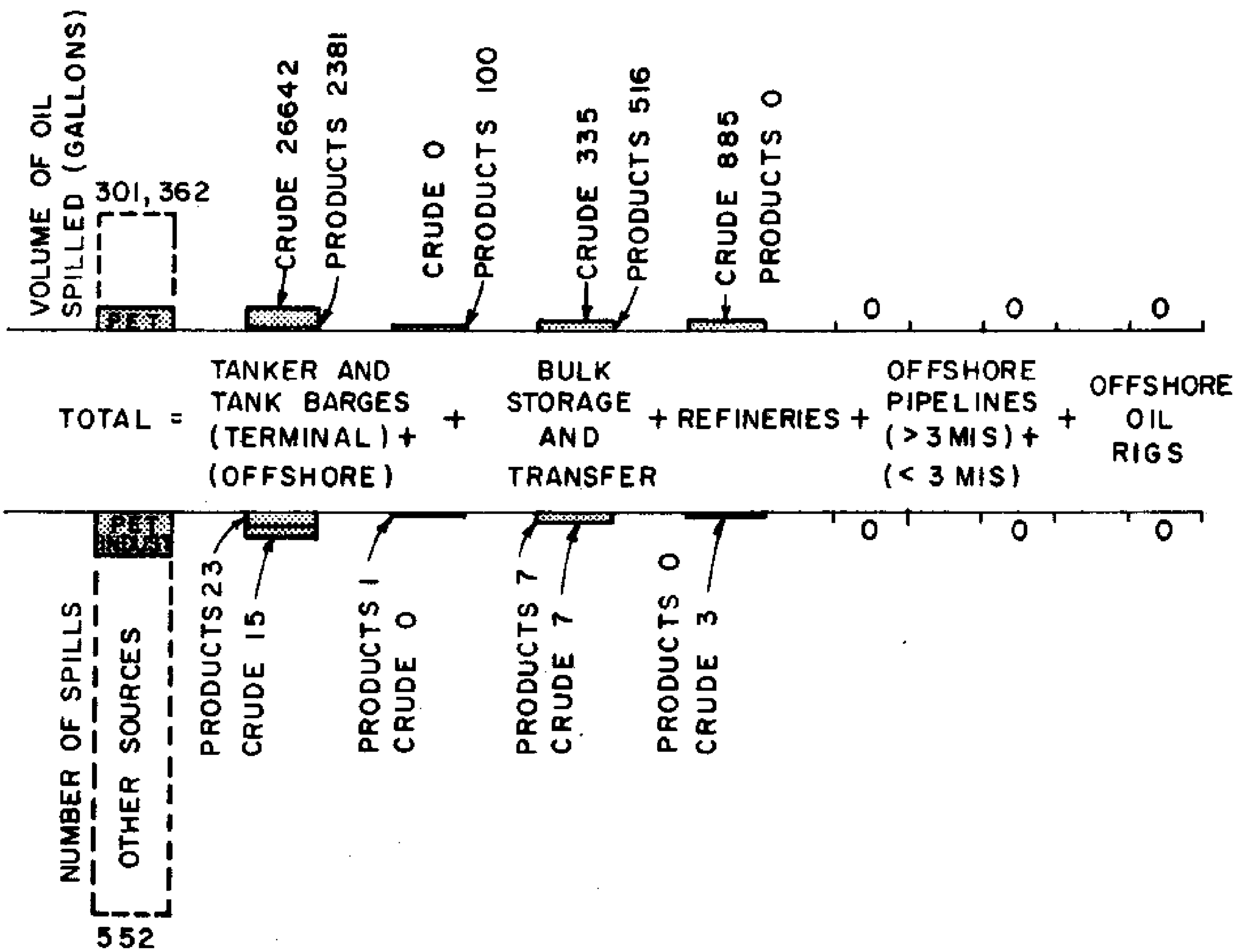


FIGURE II-1-7 REGIONAL SPILL STATISTICS FROM INDUSTRY RELATED SOURCES SOUTHERN CALIFORNIA

Of course, similar arguments may be made for some areas of New England, so it is speculative to attempt to explain the differences in the data on these grounds. Note that the amount of oil reported spilled from refineries is puzzlingly small, particularly in view of the extensive refining carried on in this region.

Figure II.1.6 summarizes the Gulf Coast spillage for 1971. Note that pipelines, refineries, and offshore oil rigs have now assumed a prominent position in the list of polluters. In particular, note that of the total of 1,363 offshore pipeline spills in the U.S., 1,350 of them occurred in the Gulf Coast region.*

Figure II.1.7 summarizes the spill reports for the Southern California region. Despite the fairly extensive refining and oil production it can be seen that only the distribution network contributed significant pollution. This can be explained by this region's traditional reliance on land-based transport of goods, and the subsequent inland location of many refineries. About the only interesting thing about this region's data is the absence of reported offshore tower spills. As we shall see shortly, Southern California does produce a substantial amount of oil from the offshore region. This apparent lack of spillage can be used to substantiate our discussion of the offshore pipeline spill problem, as the Southern California region has no nearshore development equivalent to the Gulf's, or possibly as evidence of less regular reporting of spills on the West Coast.

---

*The Gulf Coast region was taken to be the states of Mississippi, Texas, and Louisiana; plus any spills reported to have occurred three miles or more offshore in the Gulf of Mexico.

is presumed to be fixed. The data was then used as the scaling factor for the number and volume of spills from tankers and tank barges in New England (see Figure II.1.4). Since all the petroleum handled by transfer and storage facilities in New England is brought in by tanker or tank barge, the extrapolated 1971 throughput was also used to scale the transfer and storage facility spillage.

The spillage at offshore towers and pipelines was scaled by using the far offshore pipeline and the offshore tower spill data for the Gulf Coast region in conjunction with the U.S. Geological Survey's figures on yearly offshore production on the continental shelf off Texas, Louisiana, and Mississippi. Table II.1.5 summarizes the Geological Survey offshore production data for 1971. Also included is the number of wells located offshore in 1971. Among many other approaches either the total production or the total number of wells might be selected as the scaling parameter. As discussed in the introduction, we arbitrarily chose the total production rate to be consistent with our other selections. The offshore tower data includes all towers and so the total Gulf Coast OCS production figure is used. The far offshore pipelines only carry that fraction of the oil produced in the "Federal OCS" region. Therefore the gross OCS production was reduced to the appropriate fraction (86%).

The mean refinery spillage rate was based on the Gulf Coast refinery spill data and refinery capacities, since we distrusted the Middle Atlantic figures. Table II.1.5 summarizes the regional refinery capacities. An attempt was made to include only those refineries situated on the water since only their spills would be contained in the Coast Guard data. There is substantial room for error in this categorizing technique due to uncertainty in the

II.1.6 Estimates of mean spillage rates

Utilizing the 1971 spill data and the appropriate throughput figures, we are now in a position to estimate mean spillage rates for the various elements of the oil industry. We will determine the mean number of spills per year and the mean volume spilled per year per thousand barrels per day throughput.

The throughput data for the various elements of the petroleum industry for all of the U.S. is not easily determined. However, it is possible to determine the throughput for specific elements of the petroleum industry in certain regions. The New England region's ship and transfer and storage facility throughput is readily derived from the Army Corps of Engineers waterborne commodity data. The refinery, offshore tower and offshore pipeline throughput is available from various sources for the Gulf Coast. We have already broken out the spillage for these two regions in the previous section. By attacking the problem by utilizing regional spillage and throughput statistics we may reduce the number of spills in the sample and therefore increase the uncertainty associated with our estimate of the spillage. This is not a problem for the tower, or the refinery, or the pipeline, as nearly all the 1971 spillage occurred in the region selected. However, the ship and transfer and storage facility spillage in New England was less than one-tenth of the national total. In fact, we shall see that we require more data than is available in the 1971 data anyway; and the most reliable predictions appear to be those relating to the ship and storage facility spillage.

Table II.1.4 summarizes the Corps of Engineers data concerning crude and products shipment along the New England coast in 1971. The products data was extrapolated to 1971 by presuming a 4% growth rate. The crude throughput

Table II.1.4

Summary of New England Petroleum Distribution;
in 2,000 lbs. Tons Handled in 1970
(Total Receipts and Shipments)

		Crude	Products
1.	Penobscot River, Maine		1,710,712
2.	Searsport, Maine		713,080
3.	Portland, Maine	23,048,339	6,730,516
4.	Portsmouth, New Hampshire		1,268,497
5.	Salem, Massachusetts		1,245,021
6.	Boston, Massachusetts	60,380	23,966,936
7.	New Bedford, Massachusetts		521,888
8.	Fall River, Massachusetts	436,830	3,853,997
9.	Providence, Rhode Island	328,166	8,789,909
10.	New London, Connecticut		3,678,811
11.	Thames River, Connecticut		372,930
12.	Connecticut River (below Hartford)		3,794,020
13.	New Haven, Connecticut		10,570,185
14.	Bridgeport, Connecticut		3,307,648
15.	Stamford, Connecticut		611,320
16.	Beverly, Massachusetts		180,348
17.	Carvers, Maine		5,019
18.	Cobscook, Maine		17,994
19.	Cross Rip Shoals (Nantucket Island)		14,220
20.	Gloucester, Massachusetts		8,915
21.	Great Salt Pond, (Block Island)		4,757
22.	Greenwich, Connecticut		23,040
23.	Harbor of Refuge (Block Island)		1,730
24.	Harbor of Refuge (Nantucket Island)		27,867
25.	Kennebec, Maine		1,990
26.	Lynn, Massachusetts		7,622
27.	Moosabec Bar, Maine		9,713
28.	Newport Harbor, Rhode Island		97,710
29.	Plymouth, Massachusetts		43,009
30.	Rockland, Maine		6,251
31.	Seekonk River, Rhode Island		82,891
32.	Vineyard Haven, Massachusetts		35,758
33.	Warwick Cove, Rhode Island		1,138
34.	Westport, Connecticut		7,139
		23,873,715 Tons/yr.	71,712,531 Tons/yr.
		(440 Kbbl/day)	(1460 Kbbl/day)

Extrapolated 1971 throughput:

440 + (1.04) (1460) = 1960 Kbbl/day

Table II.1.4* Offshore Oil and Condensate Production, 1971

1. Total Production: (All U.S. Offshore)
2. Breakout by State

State	No. Wells	Gross Production (near and far off-shore 1000's of bbls	Percentage Produced from Federal OCS (far offshore region	Adjusted OCS Gross Production (carried by far offshore pipelines) 1000's of bbls
La.	5,429	385,760	87	335,000
Texas	101	1,685	58	980
Calif.	188	31,104	31	9,650
Gulf Coast Region (Texas & La.)	5,530	387,445	87	336,000

*Source: Harris, Walter, M., Lane, Alta, L., and McFarland, Bruce E., outer Continental Shelf Statistics, Dept. of Interior, Geological Survey, Conservation Division, April, 1972.

Table II.1.5

Regional Refinery Capacities;

Thousands of Barrels per Day

1. New England	
Mobil, Providence	7.5
2. Mid Atlantic States	
New York, New Jersey, Delaware, Pennsylvania	
(NJ)	
Humble, Bayonne	33
Humble, Linden	155
Hess, Port Reading	70
Chevron, Perth Amboy	80
Texaco, Westville	91
Mobil, Paulsboro	90.8
(PA)	
Arco, Philadelphia	160
Gulf, Philadelphia	168.1
BP, Marcus Hook	105
Sun, Marcus Hook	158
(DE)	
Getty, Delaware City	140

Source: 11 October 1971 Oil & Gas Journal Crude Oil Pipeline Atlas of U.S. and Canada 1 July 1971 figures.

Table II.1.5 Cont'd.

3.	Gulf Coast	
	(MS)	
	KYSO, Puscagoula	270
	(LA)	
	Tenneco, Chalmette	84
	Murphy, Meraux	34
	Shell, Norco	240
	Good Hope, Good Hope	8.6
	Gulf, Venice	22.7
	Lajet, St. James	6
	Texaco, Convent	145
	Continental, (Westlake)?	71
	Cities Service (Lake Charles)?	225
	(TX)	
	BP, Port Arthur	80
	Texaco, Port Arthur	320
	Gulf, Port Arthur	331.2
	Mobil, Beaumont	335
	Union, Nederland	105
	Texaco, Port Neches	53
	Union Texas, Winnie	8.1
	Humble, Baytown	345
	Texas City, Texas City	60
	Marathon, Texas City	45
	American, Texas City	325
	Eddy, Houston	2.5
	Charter, Houston	72
	Crown, Pasadena	85
	Signal Oil & Gas, Houston	70
	Champlin, Corpus Christi	52.5
	Coastal States, Corpus Christi	135
	Hess, Corpus Christi	55
	Southwestern, Corpus Christi	43.5
	Suntide, Corpus Christi	50
	Monsanto, Texas City	41
	Phillips, Sweeney	85
	P.P.G. Ind., Corpus Christi	5
	Shell Oil, Deer Park	208
	ARCO, Houston	187.5
	Total	3,880.9K b/d

Table II.1.5 Cont'd.

4.	Southern California	
	Union, Arroyo Grande	35
	Douglas, Santa Maria	6.5
	Utility, Ventura	8.5
	Edington, Oxnard	2.5
	Lunday Thogard, Los Angeles	3.0
	Douglas, Los Angeles	25
	Socal, Los Angeles	220
	Mobil, Los Angeles	123.5
	Carson, Carson	7
	Champlin, Wilmington	30
	Shell, Wilmington	86
	Arco, Wilmington	165
	Union, Wilmington	104
	Macmillan, Wilmington	10
	Edgington, Wilmington	16
	Texaco, Wilmington	77
	Fletcher, Los Angeles	10
		471.5

Table II.1.6
Estimates of Mean Spillage Rates
as a Ratio of Production and Transportation
Activity (Measured in 1000s of Bbl/Day Throughput)
Based on 1971 USCG Spill Reports

Source	Mean number of spills/year (#/year)/(1000s of bbls/day)	Mean vol spilled (gal/yr)/(1000s of bbls/day)	% spilled
Tankers and tank barges in restricted waters	.0357	(386 / 1,540)* *	(.0025 / .01)
Transfer and storage facilities	.0153	(19.8 / 200)*	(.0001 / .001)
Offshore towers	1.01	(108 / 760)* *	(.0007 / .005)
Offshore pipelines	.17	(15.8 / 160)*	(.0001 / .001)
Refineries	.0364	(51.7 / 520)*	(.0003 / .003)

*Upper value in parentheses indicates mean as estimated directly from data, bottom value gives probably upper estimate on actual value due to sample size errors (.68 confidence limit).

Table II.1.7
Quantities of Oil Spilled at Milford Haven

Year	Total Throughput 1000s of Bbls/Day	Quantity Spilled Gallons	% Spilled
1963	234	2,600	.00008
1964	318	2,400	.00005
1965	487	9,700	.00014
1966	520	8,300	.00011
1967	507	73,000	.00095
1968	709	4,500	.00005
1969	745	4,050	.00004
Average	505	10,000	.00018

physical location of the facility. The general rule was that if the refinery was located in a town that was on a channel or river (or harbor) then it was included.

Table II.1.6 summarizes the various mean spillage rates resulting from these assumptions. Note that tankers and tank barges contribute the greatest volume spilled per year per thousand barrel throughput, and that offshore towers have the most frequent spills, although they are generally small. Remember also that according to the Coast Guard data, tankers and tank barges at sea contributed a negligible fraction to the total number and volume of spills. In general, the evidence pretty clearly indicates that the bulk of the spill problem is found in two areas: tankers and tank barges in restricted waters (i.e. in the approaches to a terminal), and the offshore tower.

With respect to the 1971 USCG data, Table II.1.6 is pessimistic. When faced with conflicting evidence, we have always chosen the source which generates the higher estimate of mean spillage rates. In particular, the estimate of tanker and barge spillage rates is considerably higher than the national average. On the surface, it appears that New England is considerably sloppier than elsewhere in handling oil, and Table II.1.6 operates under the assumption that this will continue. It is interesting to contrast Table II.1.6 with the Milford Haven experience, Table II.1.7.

Our on-site visits convinced us that Milford Haven keeps at least as careful records and control as anywhere else and that the Milford Haven data is quite likely to be accurate. Milford Haven is a new port unloading crude from supertankers and loading products to 30,000-50,000 ton tankers.* As the figures indicate, the average

---

*Milford Haven also keeps data on spill incidence, which has been running at about one spill per 50 ship visit. Interestingly enough, the Milford Haven data indicates that small tankers have a slightly lower spill incidence than large. The terminal attributes this to the fact that the smaller products tankers load and unload more frequently and hence their crews are better drilled in transfer operations.

spillage rate from all sources at Milford Haven is less than one-tenth the rate from tankers and barges in New England.* Thus, Table II.1.6 is undoubtedly conservative. More importantly, the figures indicate that New England could greatly improve its spillage experience within the bounds of present technology.

From the standpoint of classical statistics, we should be reasonably confident that the mean is within the range of the bracketed terms on Table II.1.6. However, in the following section, we shall see that an interpretation of long-term historical data leads to estimates that may exceed the specified range by as much as a factor of 9. This disagreement is due to the wide distribution of the data and the necessity for obtaining significantly larger samples, particularly for offshore towers and pipelines.

---

*The transshipment terminal at Bantry Bay reports 180 gallons spilled in its history, which would put its spill incidence 1,000 times lower than Milford Haven during a good year. However, the terminal's evaluation of a spill that took place during our visit to Bantry Bay convinced us that this data is inaccurate.

Table II.1.8
Reported Tanker Spills in Excess of 42,000 Gallons, 1957-1971

Name/Location	Date	Cause	Material	Est. Spill
Torrey Canyon, Scillies	18.3.67	Grounding	Crude	29,000,000
World Glory, South Africa	13.6.68	Hull Failure	Crude	13,500,000
Keo, Massachusetts	5.11.69	Hull Failure	#4	8,800,000
R. C. Stoner, Wake Island	6.9.67	Grounding	Mixed	6,250,000
A. M. Browig, 35 mi W. Heligoland	20.2.66	Collision	Crude	5,300,000
Andron, W. Coast of Africa	5.5.68	Sinking	Crude	5,000,000
Ocean Eagle, Puerto Rico	3.3.68	Grounding	Crude	3,500,000
Polycommander, Spain	5.5.70	Grounding	Crude	3,500,000
Tampico, Baja California	.3.57	Grounding	Diesel	2,500,000
Arrow, Straits of Canso	.2.70	Grounding	Bunker C	1,500,000
Pacific Glory, 6 mi NW. Isle of Wight	21.10.70	Collision	?	1,400,000
Gen. Colocotronis, Bahamas	7.3.68	Grounding	Crude	1,300,000
Esso Essen, South Africa	29.4.68	Grounding	Crude	1,300,000
Argea Prima, Puerto Rico	17.7.62	Grounding	Crude	1,200,000
Ocean Grandeur, Australia	3.3.70	Grounding	Crude	900,000
Oregon Standard, San Francisco	18.1.71	Collision	Bunker C	840,000
Esso Gettysburg, Connecticut	22.1.71	Grounding	Ker. & #2	780,000
Otto N. Miller, 10 mi S. Beach Head	27.3.65	Collision	?	730,000
Witwater, Canal Zone	13.12.68	Hull Failure	Mixed	630,000
Benedicte, 13 mi off Trelleborg	31.5.69	Collision	Crude	590,000
Floreal, 2 mi off Gibraltar	11.9.65	Collision	?	560,000
Evje, Alaska	2.5.67	Grounding	Jet	420,000
Gironde, Off Britanny	19.8.69	Collision	?	420,000
Tim, Pennsylvania	18.2.68	Sank	#6	290,000
Efthycosts, Bristol Channel	8.3.70	Collision	?	220,000
Esso Wandsworth, Thames	23.9.65	Collision	?	220,000
Hamilton Trader, Liverpool Bay	30.4.69	Collision	Resid	210,000
Barge, New York	27.12.70	Grounding	#2	200,000
R. L. Polling, N.H.	10.5.69	Collision	#2	200,000
Marita, California	20.9.62	Collision	Bunker C	180,000
Florida, W. Falmouth, Mass.	10.9.69	Grounding	#2	172,000
Algol, New York	9.2.69	Grounding	#6	168,000
Hullgate, 4 mi off Beach Head	8.4.71	Collision	?	165,000

Table II.1.8 (continued)

Name/Location	Date	Cause	Material	Est. Spill
Monti Ulia, Coryton	27.7.70	Grounding	?	140,000
Barge, New York Bay	22.5.70	Collision	#6	131,000
Barge, Florida	26.5.70	Collision	Gas	84,000
Texacao Caribbean, 9 mi off Dungeness	11.1.71	Collision	?	84,000
Barge, Louisiana	23.5.69	?	#2	76,000
Heruluv, 2 mi ENE. South Goodwin Light Vessel	15.5.71	Collision	?	72,000
Barge, Maryland	12.7.70	Human Error	#6	67,000
Barge, Louisiana	26.5.70	Collision	Crude	67,000
Kenai Peninsula, Pennsylvania	5.11.68	Collision	Crude	42,000
Otello, Lindal Sound	20.3.70	Collision	?	"serious leakage"
Lutsk, Bosphorus	1.3.66	Collision	?	"serious leakage"
Mosli, N. Atlantic	13.7.66	Collision	?	"serious leakage"
Beefeater, Thames	5.11.68	Collision	?	"some leakage"

II.1.7 Estimates of mean amount spilled and mean time between spills by size category, based on worldwide data for the last ten years

Large spills occur much less frequently than small spills. Consequently, the sample of large spills at our disposal is much smaller than the sample of all spills. Unfortunately, the number of samples required to determine the frequency of occurrence of a rare event is many times the number of samples required to determine the probability of a common event. For example, a sample size of 200 can tell us within 90% confidence that an estimate of a probability is within 15% of the true value, provided that the estimate is in the range of .4 or above. However, if the estimated probability based on 200 samples is .01 (that is, we have noted two occurrences in 200 trials) than the actual probability may be anywhere between .001 and .02 with 90% confidence. In short, such an estimate would be reasonably likely to be off by a factor of ten or more.

Given this high level of uncertainty when dealing with large spills, it pays to increase the size of the sample even if it means introducing data of uncertain calibre. Therefore, in this section, instead of restricting ourselves to the U.S. 1971 experience, in estimating the mean time between large spills, we will use worldwide data from 1964 on.

In generating our estimates of the mean time between large, non-tanker spills, we used the Geological Survey data of Table II.1.1, restricting ourselves to spills occurring after 1964, since it appears likely that some large spills occurring earlier went unreported. With respect to tanker spills, we used data from a number of sources to compile Table II.8.1. Notice that almost all the reported tanker spills are either groundings or collisions in restricted waters, tending to substantiate the low incidence of at-sea, large tanker spills noted in the Coast Guard data. Figure II.1.8 summarizes the large tanker spill data.

Sun Oil (1971) and Fearnley and Egers (1970) data was used to estimate that the volume of oil transported by ship in the period 1965 to 1971, in and out (counting loading and discharging separately), was 41 million barrels per day. The three reported refinery spills over 42,000 gallons occurred in the period 1968 to 1971. The average refinery throughput during this period was about 24 million barrels per day. There were three outer continental shelf pipeline spills over 42,000 gallons between 1967 and 1971 and seven large platform spills, all U.S., in the period 1964 through 1971. The 1967 to 1971 annual average OCS production was 865,000 bbl/day and the 1965 to 1971 average was 700,000 bbl/day.

Finally, we note that there were fifteen spills of over 42,000 gallons between 1969 and 1971 from bulk storage and transfer facilities, for the whole U.S. We have estimated the total U.S. bulk storage and transfer facility throughput by two techniques, both relying on the New England throughput and spillage data. First we assumed that the ratio of the number of spills in New England to the total number of spills nationally (30/389) for bulk storage and transfer facilities equals the ratio of New England throughput to the national throughput. Secondly, we took the ratio of the volumes spilled instead of the number of spills (39,000 gal/500,000 gal), and equated that to the ratio of the New England throughput in 1971 (about 1,960 K bbl/day) to the national throughput. Surprisingly enough, both techniques give identical estimates of 25 million bbl/day national storage throughput, which is roughly double the annual consumption during this period.

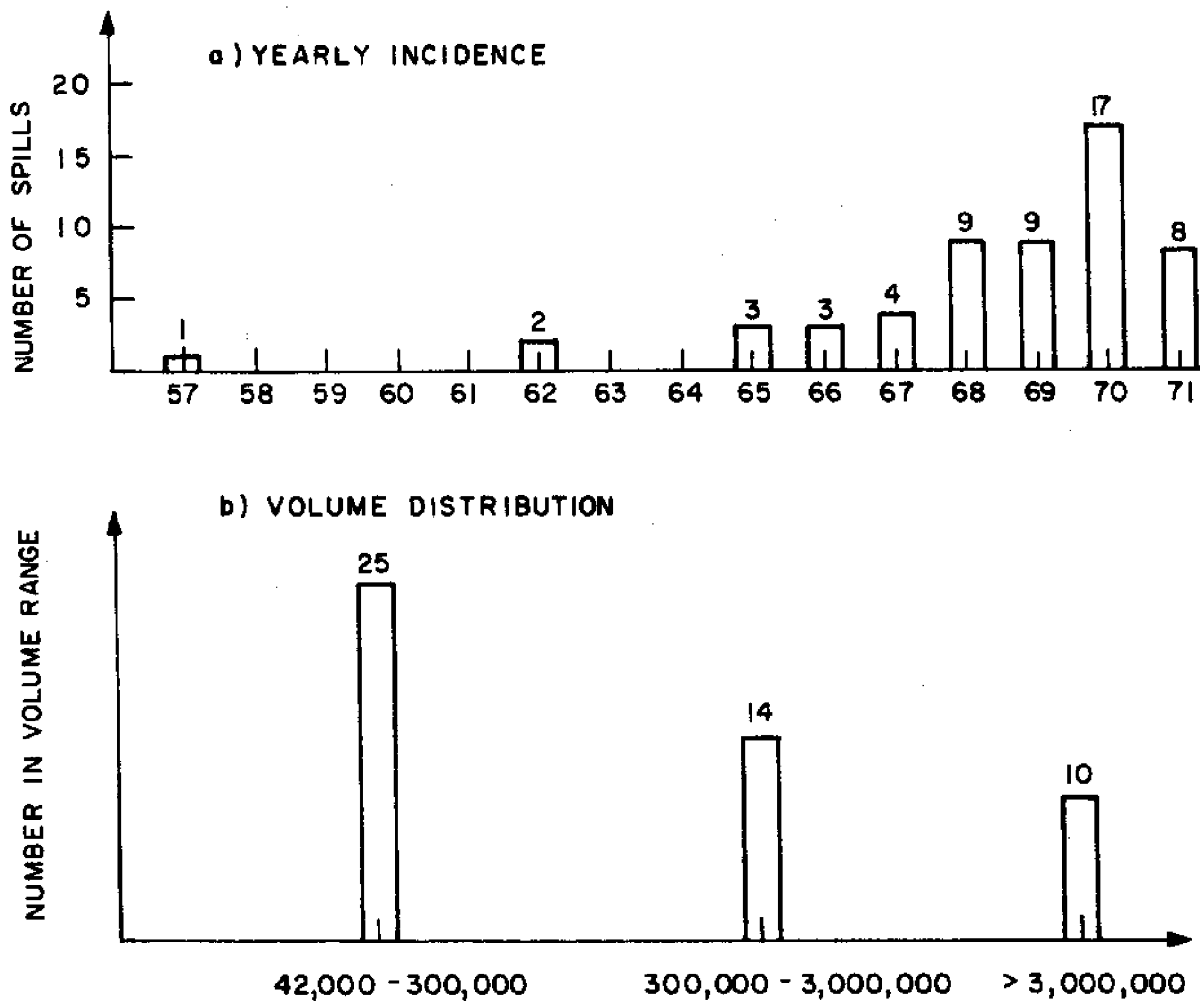


FIGURE II-1-8 SUMMARY OF OIL SPILLS OVER 42,000 GALLONS FROM TANKERS AND TANK BARGES

These volumes handled were combined with the spill data and our assumption that mean time between large spills is inversely proportional to volume handled to yield the mean rates of spill incidence shown in Table II.1.9. The tanker sample was judged to be large enough so that a breakdown into four spill size categories was warrented. However, for the other elements only a single spill size category has been computed due to the small sample size.

Table II.1.9
Estimates of Mean Rate of Incidence of Spills
42,000 Gallons

Source	Spill Size Category (Gallons)	Rate of Incidence (Spills/Yr)/ (1000 Bbl/Day)
Tankers and Tank Barges	> 42,000	.00019
	42,000 to 300,000	.00010
	300,000 to 3,000,000	.00006
	> 3,000,000	.00004
Refineries	> 42,000	.00003
Offshore Towers	> 42,000	.00109
Offshore Pipelines	> 42,000	.00069
Transfer and Storage Facilities	> 42,000	.00002

It is interesting to compare the percentage spilled from the worldwide tanker data with that arrived at from the New England Coast Guard data. Based on Table II.1.8, and our estimates of worldwide tanker volume, .003% of all the oil handled worldwide, in and out, was spilled in spills over 42,000 gallons. This estimated average was somewhat higher than that derived from the Coast Guard New England data (.0025%), which includes all spills and which in turn is considerably higher than the 1971 national average and over ten times higher than that experienced at Milford Haven. On the other hand, this is not completely unexpected since the worldwide data is dominated by a few extremely large spills and no spills of like size occurred in the U.S. in 1971. If the "Torrey Canyon" spill had occurred in New England in 1971, the estimated spill rate for New England by our procedure would have increased by a factor of 40. This, of course, is a very extreme example.

Similarly, calculations of the average volume spilled from offshore towers based on both long-term historical records and on the 1971 USCG spill reports leads to two significantly different estimates of the average spillage. Between 1964 and 1971, approximately 8 x 10^{10} gallons of crude were produced offshore. Table II.1.1 indicates that approximately 4.4 x 10^{6} gallons were spilled. This gives us an average spillage of .0055 percent, which coincides with our upper confidence limit on the mean spillage for this category,* but differs significantly from the actual 1971 average.

In the same fashion, the spillage from offshore pipelines was investigated. The results yielded an average spillage of .009 percent of the throughput, which contrasts sharply with the estimated value of .0001 percent in Table II.1.6 (the upper confidence limit was .001 percent). The magnitude of this estimate is due to the one very large pipeline spill shown in Table II.1.1. This points out that a limited sample size can cause problems in both directions. On the one hand, the small number of recorded 1971 spill incidents limits our confidence in its predictions. On the other, the small number of pipeline spills in all of history limits the confidence we can have in the historical estimate. This same statement is of course true, but to a lesser extent, for the tower and tanker spills, since their analysis incorporated more reported incidents. A similar analysis for the bulk storage and transfer facility yielded .001 percent, which coincides with the upper confidence limit.

These discrepancies are unfortunate in that they limit the confidence we can have in our predictions. In the face of this uncertainty, we have elected to generate both a

---

*Note that if we use only the 1970 data, the average spillage is a very high .025 percent.

"low" and a "high" estimate of the mean spillage for each system element. The low estimate is based on the Coast Guard 1971 estimates (Table II.1.6). The high estimate is based on the 1964 to 1971 worldwide data on large spills, except for the refinery category, where we used the upper confidence limit of Table II.1.6 rather than give full weight to a single very large spill. The resulting range of estimates of mean spillage rates is:

	Low	High	
Tankers and tank barges	.0025%	.003 %	(Worldwide data, also similar to New England region, 1971)
Transfer and storage facilities	.0001	.001	(Upper confidence limit, New England region 1971, also similar to worldwide data)
Offshore towers	.0007	.0055	(Worldwide data)
Offshore pipe-lines	.0001	.009	(Worldwide data)
Refineries	.0003	.003	(Upper confidence limit, 1971 USCG data)

Our inclination is to believe that the actual means lie closer to the high end than the low, but more than this we cannot say.

Blank Page

II.1.8 Estimates of Mean Amount Spilled and Mean Rates of Spill Incidence for a Range of Hypothetical Developments

Chapter I.2 analyses several hundred hypothetical combinations of offshore discovery, refinery location and petroleum transport systems. However, for the purposes of this chapter, it suffices to restrict our attention to nine basic possibilities. Let us consider the year 1978. One possibility is that there may have been no change in the basic characteristics of the New England petroleum system, just growth to meet demand. Secondly, a regional refinery may have been built of such a size that it can handle New England's distillate demand. Such a refinery might be located at a deepwater harbor on the Maine coast or in southeastern New England. Finally, we might have found and developed oil on Georges Bank. This find can be represented in the extremes as either a very large discovery or as a marginal discovery. Chapter I.2 indicates that if there is a refinery, and it is located in northern Maine, then all transport of crude from an offshore find will be by tanker. If the refinery is in southeastern New England, then the crude from a large find will be brought ashore by pipeline. The crude from a small find will be brought in by tanker. If there is a refinery in southeastern New England, then products distribution could well be land-based pipeline and not by tanker or barge. However, storage facilities must be provided at the refinery, so the total throughput of the transfer and storage facilities would not change regionally. Finally, we may have discovered a sizable gas find and little oil.

Table II.1.10 summarizes the 1978 throughput, in and out, for the various elements of the petroleum industry for eight possible combinations of these assumptions. The basic demand figures from which this table is derived includes 440,000 bbl/year of crude into Portland and a regional product demand of 1,600,000 bbl/year in 1978. This represents

Table II.1.10
Estimated Regional Throughput In and Out for Eight Representative Development Plans in 1978 @ 4% Growth

Plan No.	Description	Refinery Thruput	Bulk Storage & Transfer Facilities Thruput Bbl/Day	Pipeline Thruput Bbl/Day	Offshore Tower Production Bbl/Day	Tanker and Tank Barge Thruput Bbl/Day
1	No Find No Reg. Ref.	0	2,400,000	0	0	2,400,000
2	No Find Reg. Ref. Pres. PDS	1,025,000	2,400,000	0	0	4,600,000
3	No Find Reg. Ref. Pipeline PDS	1,025,000	2,400,000	0	0	2,040,000
4	Large Oil Find No Reg. Ref.	0	2,400,000	0	1,000,000	2,400,000(+)
5	Small Oil Find Reg. Ref. Pres. PDS	1,025,000	2,400,000	0	100,000	4,600,000(+)
6	Small Oil Find Reg. Ref. Pipeline PDS	1,025,000	2,400,000	0	100,000	2,040,000 (+)
7	Large Oil Find Reg. Ref. Pres. PDS	1,025,000	2,400,000	0	1,000,000	4,600,000(+)
8	Large Oil Find Reg. Ref. Pipeline PDS	1,025,000	2,400,000	1,000,000	1,000,000	1,040,000

Note: (+) indicates we are neglecting additional ship traffic incurred at the offshore drilling site.

no growth in Canadian crude and approximately 4%/annum growth in products. The amount shipped and handled by transfer and storage facilities is greater than the demand because of transshipment from primary ports like Boston. It is presumed that the ratio of total shipments to product demand is the same as in 1970, when the ratio was $(\frac{1,460}{1,200}) = 1.22$. The refinery, where it is included, is presumed to manufacture all of New England's demand except for residual fuel. Resid is presumed to be brought in by tanker or tank barge and is presumed to be 36% of the total demand, or 575,000 **bbl/day in 1978**.

Table II.1.11 presents the estimates of the mean amount spilled in 1978 and the mean number of spills which result from our assumptions for each of the nine hypotheses. Table II.1.11 deserves some careful attention, not for the exact numbers involved, but rather for the relative orders of magnitude. First, it's clear that the great bulk of the mean spillage is generated by tanker and barge traffic, whatever the hypothesis. Thus, those hypotheses which result in decreased regional tanker traffic generate the lower totals. The pipeline-based products distribution system appears especially favored by this fact.

The regional refinery in itself does not generate a great amount of spillage on the average. However, unless it is combined with a pipeline products distribution system, the additional regional tanker traffic induced by the refinery is quite significant. Finally, even a large oil find on the Bank adds at most 8% to the estimate of the amount spilled within the region and, if combined with a pipeline, actually reduces the mean amount spilled due to the reduction in tanker traffic. However, in terms of numbers of spills, rather than volume, even a small find will increase regional spill frequency considerably according to the assumptions and data we used.

It should be remembered that this is the situation in 1978 which, according to our assumptions, is a peak

Table II.1.11

Estimates of Mean Spillage for the Eight Representative Hypothetical Developments in 1978
Based on Mean U.S. Spillage Rates of Table II.1.6 and 4% Consumption Growth 1970-1978

Plan No.	Description	Refinery	Bulk Storage	Pipeline	Tower	Tanker, Barge	Total
1	No Find No Reg. Ref.	0	37spills 48,000 * 480,000	0	0	86 spills 930,000	980,000 * 1,410,000
2	No Find Reg. Ref. Pres. PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 480,000	0	0	164 spills 1,770,000	1,870,000 * 2,780,000
3	No Find Reg. Ref. Pipeline PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 480,000	0	0	73 spills 788,000	889,000 * 1,798,000
4	Large Oil Find No Reg. Ref.	0	37 spills 48,000 * 480,000	0	1,010 spills 108,000 * 850,000	122 spills 1,310,000	1,466,000 * 2,640,000
5	Small Oil Find Reg. Ref. Pres. PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 480,000	0	101 spills 10,800 * 85,000	168 spills 1,810,000	1,920,000 * 2,900,000
6	Small Oil Find Reg. Ref. Pipeline PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 430,000	0	101 spills 10,800 * 85,000	77 spills 825,000	937,000 * 1,920,000
7	Large Oil Find Reg. Ref. Pres. PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 480,000	0	1,010 spills 108,000 * 850,000	200 spills 2,160,000	2,370,000 * 4,020,000
8	Large Oil Find Reg. Ref. Pipeline PDS	37 spills 53,000 * 530,000	37 spills 48,000 * 480,000	170 spills 15,800 * 1,420,000	1,010 spills 108,000 * 850,000	37 spills 400,000	625,000 * 3,680,000

Spills are measured in gallons

*Parentheses indicate high and low estimates for average volume spilled annually from the indicated source. Statistically, the high tower, refinery and bulk storage spill estimates are feasible extrapolations from the lower value due to sample size problems. The higher value for pipelines is outside the anticipated confidence interval, but is substantiated by historical data.

production year for the offshore discovery. In later years, the other categories will continue to increase at the consumption growth rate, while the offshore production remains constant and then declines, so Table II.1.11indicates the peak effect of the offshore find on mean spillage.

Table II.1.12addresses the issue of the large spill, which we have seen has to be distinguished from the total volume spilled. Table II.1.12presents our estimates of the mean time between large spills for each system element for oureight development hypotheses. Remember these estimates can easily be off by a factor of two or more, so once again it is the relative magnitudes rather than the actual numbers that count.

Once again, the refinery and the storage element in itself is relatively unimportant. However, we now note in comparing the 42,000 gallon spill frequency that the large offshore find is the principle contributer, with a mean frequency approximately double the projection of the present system. The large find and pipeline combination has a mean frequency more than five times that of the tanker and barge system which would exist in conjunction with the pipeline-serviced find, largely due to the decrease in tanker traffic resulting from the find and the pipeline distribution. On the basis of frequency of total spills over 42,000 gallons, development plan number 8, which appeared most attractive on the basis of estimated mean spillage, is least attractive, with an overall estimate mean large spill frequency four times that of the projection of the present system. This is due to the fact that the bulk of the oil spilled by this hypothesis is in large spills while the bulk of the oil spilled by the more tanker-based hypotheses is in either small (transfer) spills or in very large (grounding, collision) spills.

This paradox raises some interesting problems for regional public officials, for it appears that spills from the offshore find will make the papers considerably more

Table II.1.12
Estimates of Mean Time Between Large Spills By Size Category
Based on Worldwide Data (Table II.1.8)

Plan No.	Description	Refinery >42,000	Stor. & Trans. >42,000	Pipeline >42,000	Tower >42,000	Tanker & Barge >42,000	Tanker & Barge >300,000	Tanker & Barge >3,000,000	Overall >42,000
1	No Find No Reg. Ref.	-	18.1	-	-	2.2	4.4	11	2.0
2	No Find Reg. Ref. Pres. PDS	30	18.1	-	-	1.2	2.4	6	1.1
3	No Find Reg. Ref. Pipeline PDS	30	18.1	-	-	2.6	5.2	13	2.1
4	Large Oil Find No Reg. Ref.	-	18.1	-	.9	2.2	4.4	11	.6
5	Small Oil Find Reg. Ref. Pres. PDS	30	18.1	-	9.2	1.2	2.4	6	1.0
6	Small Oil Find Reg. Ref. Pipeline PDS	30	18.1	-	9.2	2.6	5.2	13	1.7
7	Large Oil Find Reg. Ref. Pres. PDS	30	18.1	-	.9	1.2	2.6	6	.5
8	Large Oil Find Reg. Ref. Pipeline PDS	30	18.1	1.4	.9	5.2	10.3	26	.46

References

Covey, Charles W., "Open Sea Oil Skimmer", Under Sea Technology, August 1972.

Department of the Army, Corps of Engineers, Waterborne Commerce of the United States, Calendar year 1970.

Milford Haven Conservancy Board, The Port of Milford Haven, 1970

National Petroleum News, "U.S. Refineries and Capacities, Factbook Issue, Mid-May 1972.

Smithsonian Institution, Center for Short-lived Phenomena, Oil Pollution Event Cards, March 1968 through 9 August 1972.

U.S. Department of the Interior, Geological Survey, Conservation Division, Outer Continental Shelf Statistics, 1953 - 1971, April 1972.

U.S. Department of the Interior, Geological Survey, "Recorded Oil Spill Incidents involving 1000 or More Barrels, Since 1957", Tabulation prepared July 29, 1971, Revised 31 Dec. 1971.

U.S. Coast Guard, Commandant (WEP), Washington, D.C., "Pollution, Spills in U.S. Waters - 1970", Sept. 1971.

U.S. Coast Guard, Commandant (WEP), Washington, D.C., 1971 Spill Report Data in Punched Card form, received June 1972.

Chapter II.2
Potential Spill Trajectories

II.2.1 Introduction

A spill can be transported many miles through the action of the wind and current, as well as through its own tendency to spread. Regions of high spill probability are therefore not only local problems, but also an "upstream" source of oil that can affect places many miles away. The prediction of what is upstream and what is downstream in the flat, windblown expanses of the ocean requires an understanding of how the wind, waves and current work to push a slick around. The spreading of the oil is also important, because the areal extent of a slick will dictate the width of the path that the oil will sweep, and subsequently how much oil will be deposited on a given length of shore.

II.2.2 Mechanics governing spreading

Spills can occur in two fashions. They can be the result of some nearly instantaneous release, such as the rupture of a tank, or they can be the result of a long-lasting, continuous release, such as that which occurred in the Santa Barbara oil spill. The distinction is based on the time scales involved, which in turn are dictated by the volume and character of the oil as well as the physical dimensions of the spill region. The physics governing the spread of the oil is of course the same, but subtle differences will exist in the time dependency. For our purposes it is sufficient to examine just the instantaneous type as it is the simpler of the two.

Consider now a volume of oil suddenly dropped on the surface of the sea. Presume that there are no restraints on the boundaries of the oil, that is, that it is free to spread in all (horizontal) directions. It will be found that the oil spreads at three different rates, depending on when we look at the spill. Each rate is determined by a unique balance involving various properties of the oil and the water. The first two spreading rates involve balances between the buoyancy-induced spreading force, and first the oil's inertia, then later the water's viscous drag. The third spreading rate is due to a balance between the surface tension spreading force and the water's viscous drag. It is convenient, therefore, to consider the following three distinguishable phases in the spill's history: an inertial (spreading) regime; a viscous (spreading) regime; and finally a surface tension (spreading) regime.

These regimes will persist for varying lengths of time, depending on how much oil is initially released. Figure II.2.1 depicts the varying intervals as a function of the spill volume for a typical crude oil. The solid line at the right indicates the time at which we expect all spreading to cease. This is an observed phenomenon,

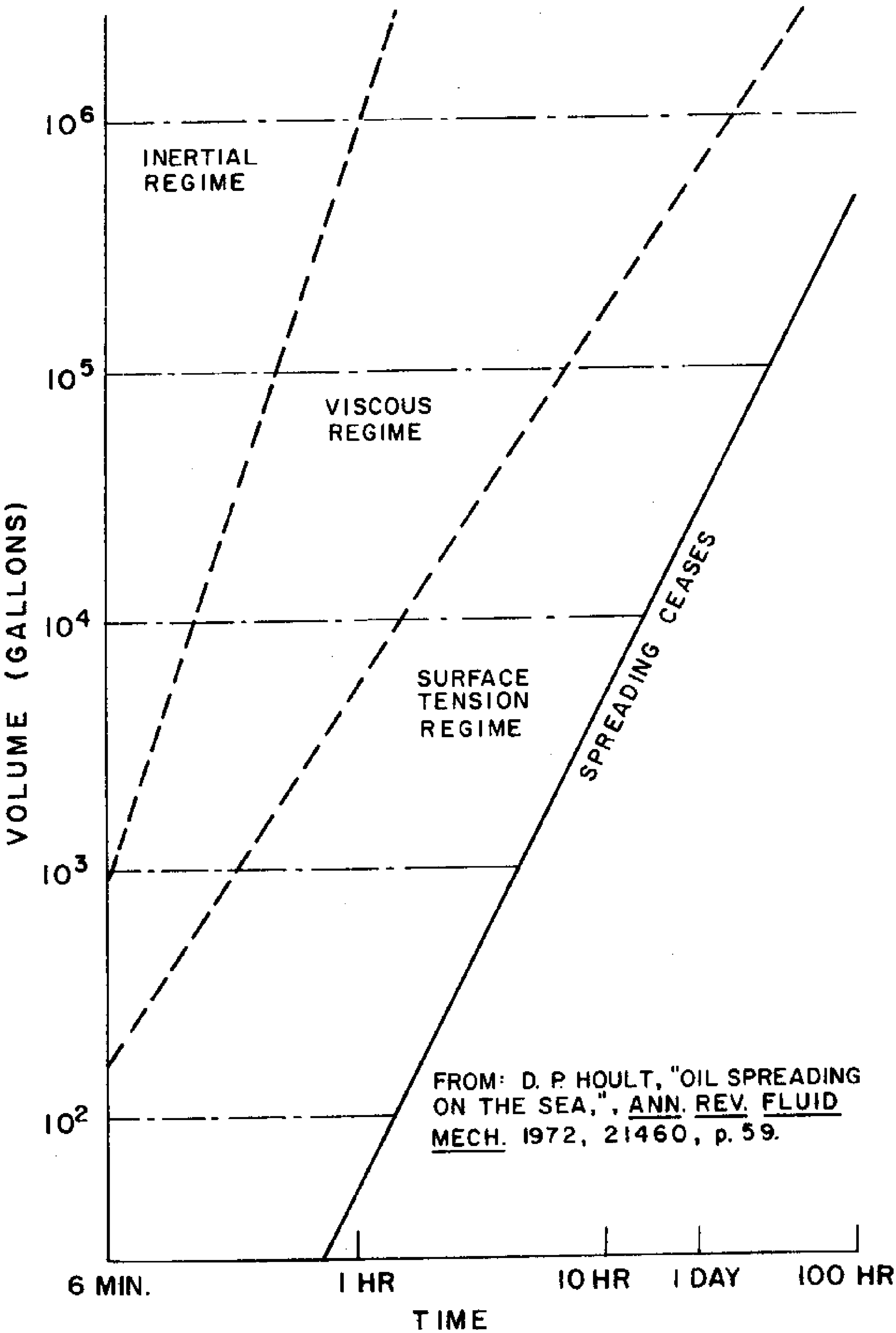


FIGURE II-2-1 SPREADING REGIMES FOR A TYPICAL CRUDE OIL and various theories have been developed to explain it. One of the more successful theories was developed by Fay (1971) in which he presumed that the hydrocarbons responsible for the observed surface tension are lost through either evaporation into the air, or dissolution into the water.

Figure II.2.2 traces the history of the growth of a spill for several spill volumes, depicting the area covered as a function of time. Again, typical crude oil properties were presumed. Table II.2.1 summarizes the various formulas used to generate these figures. Time is measured in hours, volume in gallons, and area in square miles.

In addition to these well-documented spreading phenomena, an oil spill exhibits two other properties that have a qualitative importance to our study. At some time during the spreading process,variations in the wind, waves, and current usually cause the large contiguous spill to break into several large patches surrounded by many smaller patches. The large patches will tend to separate from one another as time goes on. This will increase the width of the path swept by the spill. Additionally, the action of breaking waves on the open ocean, or of surf near shore, may cause a portion of the oil to be mixed into the water column. The importance of this behavior is that the tiny oil droplets suspended in the water can substantially increase the surface area available for diffusion of the oil hydrocarbons into the water, and they can find their way into the less mobile biota on the bottom.

Quantitative prediction of these latter two phenomena is beyond our capabilities at present. The model required to estimate the rate at which the large patches will separate from one another is presently the subject of considerable controversy. Various diffusion "laws" have been proposed, but it has been shown that no one law adequately describes a broad spectrum of behavior. In

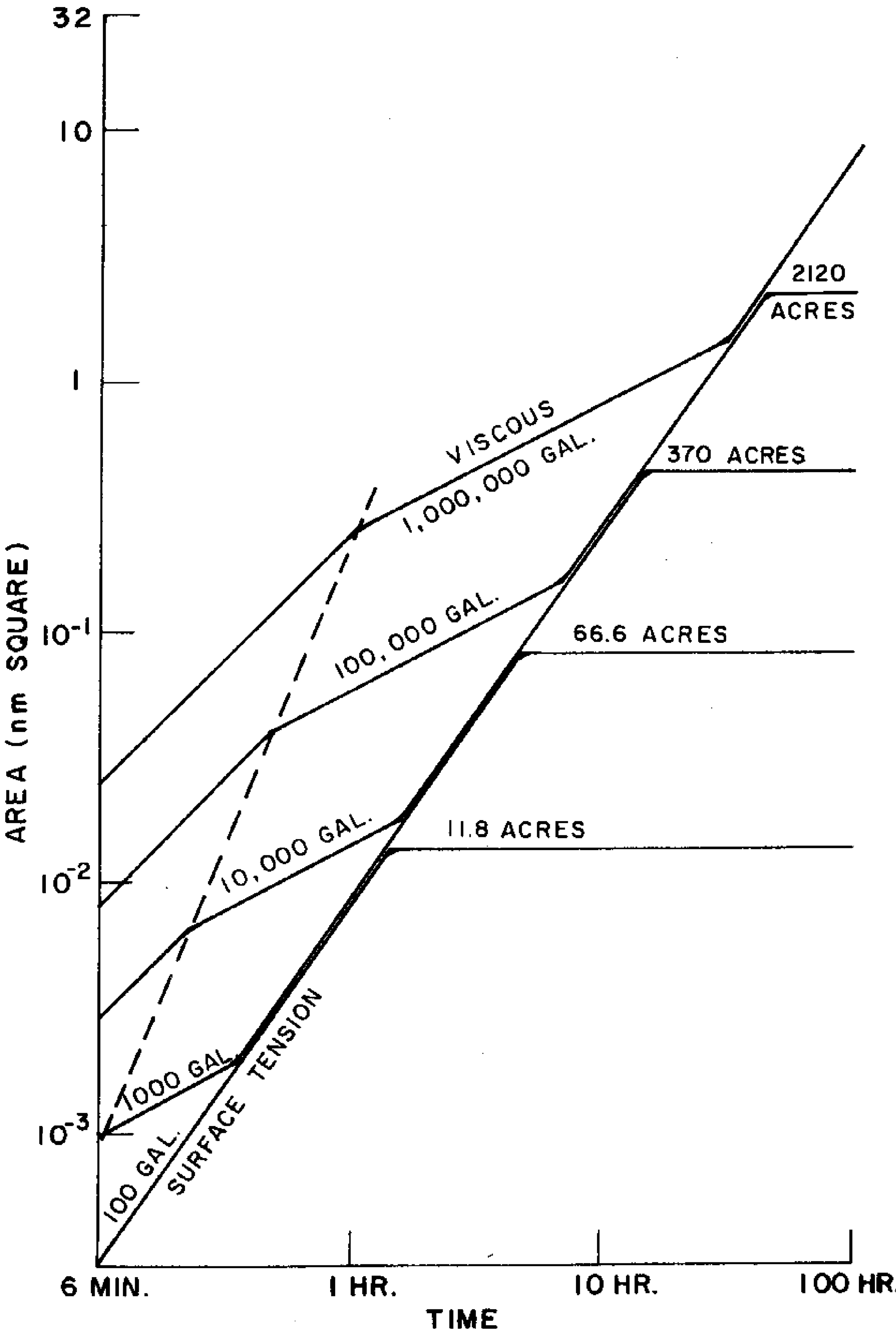


FIGURE II-2-2 REPRESENTATIVE SPREADING HISTORIES FOR FIVE SPILL VOLUMES, AREA COVERED VS. TIME FROM SPILL TYPICAL CRUDE OIL CHARACTERISTICS

Table II.2.1

1. Inertial Spreading

   a) Spreading law:

$$\ell = 1.14(g\Delta V)^{1/4}t^{1/2}$$

   b) Area:

$$A(\text{sq NM}) = 2.91 \times 10^{-4}t(\text{hours})V^{1/2}(\text{gallons})$$

   c) Regime ends when

$$\left|\frac{V^{1/2}}{[\nu t]^{1/4}}\right| = 1.14(g\Delta V)^{1/4}t^{1/2}$$

2. Viscous Spreading

   a) Spreading law:

$$\ell = 1.45\left(\frac{\Delta g V^2 t^{3/2}}{\nu^{1/2}}\right)^{1/6}$$

   b) Area:

$$A(\text{sq NM}) = 2.5 \times 10^{-5}V^{2/3}(\text{gallons})t^{1/2}(\text{hours})$$

   c) Regime ends when

$$\left|\frac{V^{1/2}}{\left[\frac{\sigma}{\rho g\Delta}\right]^{1/4}}\right| = 1.45\left(\frac{\nu g V^2 t^{3/2}}{\nu^{1/2}}\right)^{1/6}$$

3. Surface Tension Spreading

   a) Spreading law:

$$\ell = 2.30\left(\frac{\sigma^2 t^3}{\rho^2 \nu}\right)^{1/4}$$

   b) Area:

$$A(\text{sq NM}) \simeq 8.7 \times 10^{-3}t^{3/2}(\text{hours})$$

   c) Final area:

$$A(\text{sq NM}) \simeq 5.8 \times 10^{-4}V^{3/4}(\text{gallons})$$

Table II.2.1 (continued)

where:

ℓ = radius of circular pool of oil

g = acceleration of growth

$\Delta = \dfrac{\rho\,\text{water} - \rho\,\text{oil}}{\rho\,\text{water}}$

V = volume in gallons

t = time in hours

ν = kinematic viscosity of oil

A = area

σ = net surface tension at air-water-oil interface

ρ = density

actual spill incidents, this is of little importance because each large patch can be tracked individually. Only for a predictive study such as ours is this a serious shortcoming.

The suspension of oil droplets in the water column is related to the turbulence observed in the surface layer. The nature of the dependence of the suspending phenomenon on the turbulence is only qualitatively understood. Moreover, the dependence of the turbulence upon the surface waves and wind is unknown. We do know that the energy that the wind imparts to the surface waves is much greater than that which it imparts to the turbulence near the surface. The turbulence is given access to the waves' energy when waves break, so in winds great enough to cause whitecaps the surface turbulence increases substantially. The depth to which this strong wave-induced turbulence penetrates varies. Phillips (1966), warning that the available data is fragmentary, states that the depth is proportional to the wavelength and cites some published results which indicate that 10 to 30 meters might be a representative range for the depth of penetration of the strong wave-generated surface turbulence.

Oil particles will respond to this turbulence as a function of their size, because the rise velocity of a small droplet will be much less than the rise velocity of a large droplet. Utilizing Stokes' formula for the drag on a sphere at low Reynolds numbers it can be shown that the requisite power actually goes as the diameter to the fifth power. Thus, the maintenance of a droplet one-tenth the size of another at some specified depth will require one-one hundred thousandth the power. This implies that we can expect small droplets fairly deep, while large droplets should remain near the surface.

Forrester (1971) studied the distribution of oil particles following the "Arrow" grounding in Chedabucto

Bay, Nova Scotia, on February 4, 1970. The technique used was to make tows with a Clarke-Bumpus plankton sampler. This net-like device could catch particles down to about .1 mm (1×10^{-4} meters) in diameter. Additionally, 32 one-liter samples of water were obtained using Knudsen bottles. This latter sampling technique yielded data on particles down to 5μ (5×10^{-6} meters) diameter. The pertinent conclusions are contained in Table III of the Forrester's report. In it, Forrester presents the equivalent concentrations obtained by comparing the mass of oil in a given volume to the mass of water. The extremes of the data indicate that concentrations of 10 to 20 ppb can obtain to depths of 10 m; 3 to 0.5 ppb to depths of 30 m; and, in the deepest samples taken, .2 ppb at 70 to 80 m.

Summarizing, formulas have been presented which describe the spread of oil on the surface of the water. The initial rate of spread is dependent upon the volume spilled and is characterized by two distinguishable spreading regimes. A third spreading regime is encountered once the thickness of the spill decreases to a point where the outward pull of surface tension exceeds the buoyancy effects. The spill finally ceases spreading and a predictive equation has been presented to describe this. Additionally, the tendency of the spill to break into patches and the turbulent mixing of oil into the water column have been discussed. In both cases, predictive models do not appear to be available.

II.2.3 Trajectory of spill

Wind blowing over the water's surface imparts momentum to the water and causes complex motions throughout the water column. In the very top layer of the water column this motion, when compared to the motion of the rest of the water, will be in the direction of the surface wind, and it will remain so as long as the wind continues to blow (as long as the constant shear layer is maintained). Should the wind die, then Ekman's formula leads us to expect that the water at the surface will be entrained by the underlying water and it will undergo complex cyclic motions at the inertial frequency, which at the latitude of the Gulf of Maine is about 1 cycle per 18 hours. The details of this no-wind motion are complex and of little interest to us, because the net transport is small. The motion while the wind blows is of importance, however, because substantial transport of the surface layer of water can occur.

In order to specify the magnitude of the velocity of the surface layer, it would seem to be necessary to relate wind speed and wave conditions to the amount of momentum imparted to the water. Achieving this in a detailed way is not yet possible. In fact, the very mechanism by which the momentum is transferred through the water is not fully understood. It is possible, however, to make a reasonably accurate estimate of the net effect of all these phenomena by assuming that the air and the sea behave similarly, and that the ratio of the square root of the densities of air and water will be the scaling factor determining the velocity of the water at the surface with respect to the velocity of the wind measured away from the immediate effects of the water (say 10 m high). Based on this, the velocity of the surface layer (SL) will be about 3/100 of the velocity of the wind (SW).

$$\vec{U}_{SL} \simeq (.03)\vec{U}_{SW}$$

This analysis so far has not considered the behavior of the surface water when oil is present. Oil has a calming effect on waves, and it might be expected that some reduction in the transport would occur due to the smoothing of the surface. This is not the case, however, because waves generally are created by the wind and move with the wind. The action of damping waves actually imparts additional momentum to the oil. It is found that the oil should actually drift a bit faster than expected (Phillips, 1966, pp. 39-42).

It must be remembered that the surface drift due to the wind has been taken with respect to the bulk of the fluid lying under the surface layer. If this fluid is moving under the action of a current, the net motion will be the vectorial sum of the two velocities. Putting all this together, we arrive at the following formula, which applies to the center of mass of the oil slick:

$$\vec{U}_{oil} = \vec{U}_{current} + (.03)\vec{U}_{SW}$$

This formula has proven to be consistent with laboratory and field observations (Hoult, 1972).

II.2.4 Current data

In addition to wind-driven surface movement, we must consider water motion due to semidiurnal tidal excursions and much longer-run, steady state currents due to macroscopic variations in the density of the water, the so-called geostrophic currents.

Chapter II.1 identified two regions as being the most important from the standpoint of spill hazard: the coastal terminal areas and the hypothetical drilling sites on the Georges Bank. For the nearshore terminal areas, the tidal currents will assume primary importance. Peak tidal velocity will range from about a knot to five or six knots, depending on location, while geostrophic currents rarely approach .5 knots in magnitude and are generally considerably less.

In a harbor or a bay, a 5 to 10 mile tidal excursion is sufficient to wash a slick from shore to shore. On the Georges Bank, however, the distances to shore vary from 60 to 200 nautical miles. Thus, the tidal excursions, which are elliptical paths of roughly 5 miles in radius, assume a secondary importance to the net drift caused by the wind and the geostrophic current.

As part of the study effort, a thorough search was made of federal and private data sources relating to the tidal and geostrophic currents in the region of interest. In general, the results were somewhat disappointing.

i) Tidal currents: tidal current charts are available for Boston Harbor, Nantucket Sound, Buzzards Bay, Narragansett Sound, Block Island Sound and Long Island Sound. Tidal currents are also indicated for the Bay of Fundy on Chart H.O. 609, U.S. Naval Oceanographic Office. This coverage gives us information on about one-half of the inshore region. Also, the Maine-New Hampshire coast is not covered at all. This is a serious flaw because the near-shore problem for Maine is of great importance due to the interest in establishing oil handling terminals in Maine.

Coast and Geoditic Chart 1107 indicates tide roses for several locations on the Bank itself. Otherwise, we have no information on the tidal currents offshore.

ii) Geostrophic currents: there are three sources of data relating to geostrophic currents - records of ship logs compiled into pilot charts, drift bottle recoveries, and calculations based on water densities.

Pilot charts: pilot charts are available for the North Atlantic. These charts include estimates of currents in the offshore New England region. The current data is obtained from ships logs by comparing a ship's actual travel to that which one would predict from its course and speed. We obtained the source data from NOAA and it is our estimation that this analysis is highly speculative. Basically, one is looking for a rather small effect (currents of .3 knot or less) in the face of considerably larger tidal currents. Rather small navigational errors or wind effects could completely obscure the geostrophic current. The number of samples available for a given season and grid location is far from impressive, of the order of 10. Finally, the individual samples demonstrate considerable variability, as might be expected. However, the total number of samples taken in aggregate is approximately 6,000 and in aggregate, these samples do show a pattern indicating a SW drift on the southern portion of the Bank. The pilot chart estimates this drift at .4-.5 knots. This estimate is obviously subject to considerable error. We do not believe anything useful can be said about the currents in the northern part of the Gulf of Maine from the ship log information due to the sparsity and variability of the data. Figure II.2.3 presents examples of the New England portion of these pilot charts for the four monthe, January, May, August and November.

Drift bottle information: considerable drift bottle data has been accumulated on the Gulf of Maine region. A drift bottle is basically a soda pop bottle, weighted to be nearly neutrally buoyant, containing a message offering the finder a nominal reward for mailing an enclosed postcard. Various configurations have been released since they were first implemented in 1922. The problem with accepting the data from these bottles at face value are the following:

a) A certain percentage of bottles may wash ashore and break.

b) Some bottles may wash ashore and then be refloated on the next tide to be washed ashore again (or not at all) farther downstream.

c) The time of finding and even the probability of finding will depend on how populated the beaches are.

d) Some finders might simply save the bottles as quaint mementoes, while others might destroy them as a lark.

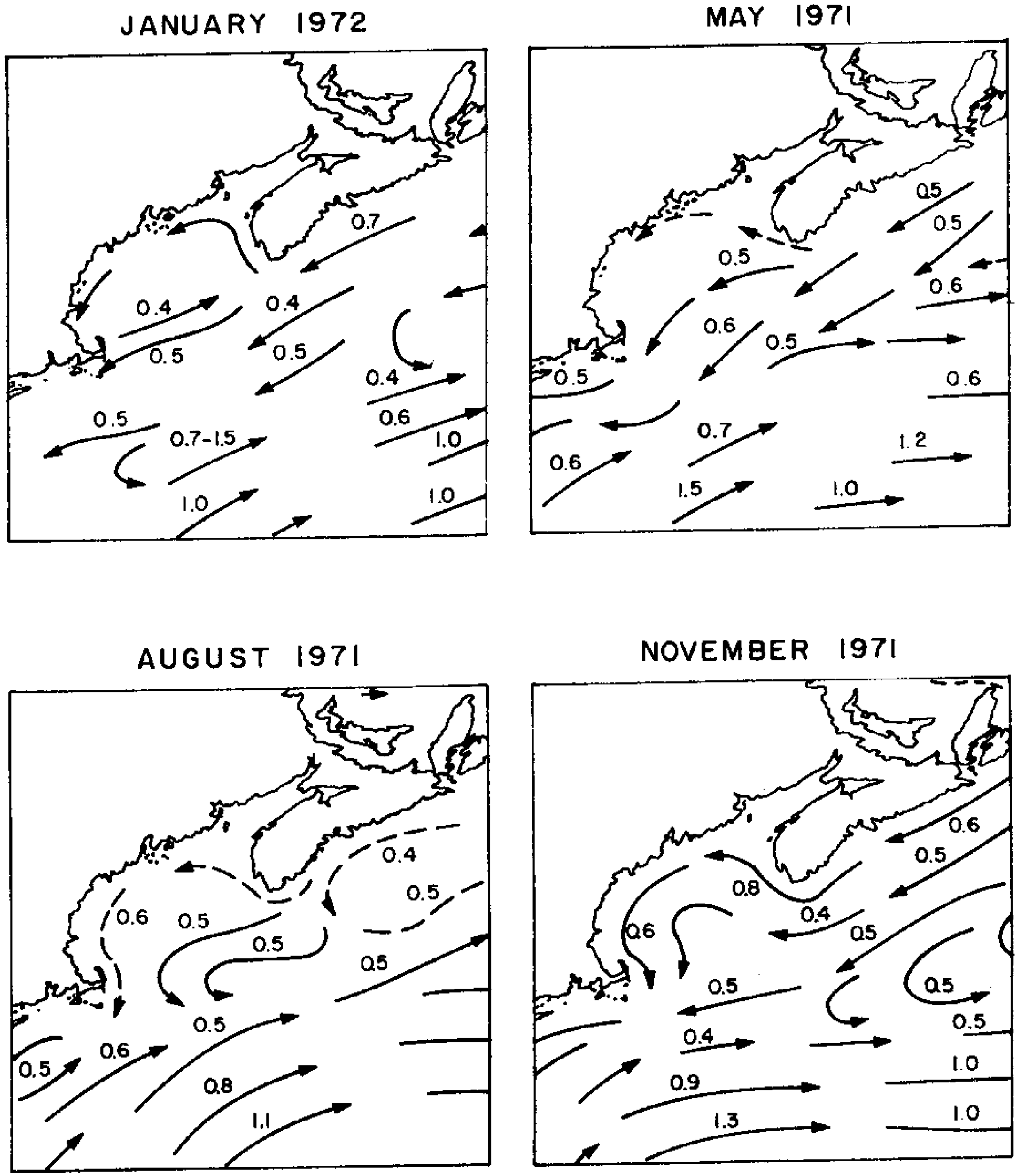


FIGURE II-2-3 PILOT CHART SURFACE CURRENT REPRESENTATIONS

e) Each individual bottle gives almost no clue as to the route it took in going from the launch point to the recovery point.

f) Drift bottle movements are affected by wind-driven surface layer and thus yield only an indirect clue as to the underlying geostrophic current.

Counterbalancing these objections are the very number of bottles released (19,997 from the Georges Bank region alone since 1922), and the diligent reconstruction effort made by the various investigators. The culmination of much of this work is the atlas authored by Bumpus and Lauzier (1967) entitled: Surface Circulation in the Continental Shelf of Eastern North America Between Newfoundland and Florida. Unfortunately, this work did not include probabilities of recovery and the various surface currents shown can be thought of as just one possible path out of many possible paths. Bumpus will shortly publish a new report dealing with overall probabilities of recovery, but still the problem of determining trajectory probability will persist.

Based partially on the drift bottle data and partially on oceanographic intuition, a rather widely accepted theory on the circulation of the Gulf of Maine has developed. This theory postulates a counterclockwise gyre in the northern portion of the Gulf which develops in early spring and breaks down in the fall. This circulation is accompanied by a smaller clockwise gyre on the Bank itself.

This circulation is generally consistent with the fragmentary evidence we have. There is solid evidence for a generally southwesterly littoral drift along the northern New England and Nova Scotia coast, and both the ship log and drift bottle data indicate a SW drift on the southern side of the Georges Bank. However, the quantitative magnitudes of these drifts and the actual structure of the offshore circulation is far from clear from the available data, due principally to the facts that knowledge of the release point and recovery location of a drift bottle does not establish its trajectory, and that we are dealing with a highly seasonal process on the basis of less than 2% overall recovery. We shall see that the fine structure of the circulation south of the tip of Nova Scotia is particularly critical to the problem at hand. The plain truth is that at this level, we know almost nothing about the actual current structure. In the face of this uncertainty, we have chosen to perform our analyses over a range of possible geostrophic current patterns:

a) in order to determine what portion of the current structure is critical to our results and

b) in order to determine if we could rule out certain current patterns as inconsistent with the data.

iii) Another possibility that has been investigated for determining currents in the Gulf of Maine was through consideration of the distribution of mass in the waters of the Gulf of Maine - the driving mechanism for geostrophic currents. If one part of the Gulf contained water that was heavier (denser) than another, then currents would have to exist to support this imbalance. This technique is speculative as it only gives currents relative to some baseline, but it seemed promising. Bigelow (1928) did considerable work in this regard and showed some interesting dynamic height contours which are consistent with a rather uniform southwesterly flow throughout the Gulf. A review of the literature was made in hopes of finding a more recent validation of his findings. The most recent compilation of the hydrography of the Gulf is given by Colton (1968), and he did not attempt to reduce the temperature-salinity data to seawater density. Nevertheless, a comparison of data taken one year apart shows considerable variation in the isotherms and isohalines which leads us to suspect that a good deal of data, spread out over many years, will be required to establish a reliable statistical base.

II.2.5 Wind data

The available data on winds is considerably more complete, and the real question here is to determine what statistics we ought to use in modeling the wind. It has been traditional to consider only the mean wind properties in air quality studies. This has led to much emphasis on the wind rose as the principal statistic. The wind rose gives us the probability that at any arbitrarily selected time the wind will be blowing from a particular direction at a mean speed (or perhaps in one of several speed ranges). If the phenomenonwe are interested in is short-lived, say on the order of minutes or hours, this may be acceptable (for example, the fall-out of soot from a chimney in the region immediately adjacent to the chimney). However, if the phenomenon lasts for several hours of more, then the changes in the wind should become important. If we looked at a large number of tests, we would expect the majority of samples to congregate around some mean drift, with some percentage wandering off away from the mean. This behavior, and particularly the deviation from the mean, is not simulated by wind rose statistics.

We have chosen, rather, to model the wind as a random process. The wind records from Nantucket Island Airport and Portland (Maine) Airport were obtained for four-year periods in the late sixties from the National Climatic Center in Asheville, North Carolina. These records were broken out into the traditional eight directions (N, NE, E, SE, S, SW, W, NW) as well as calm, and the persistence of the wind in each direction was determined. This data is summarized in Table II.2.2. The average persistence is on the order of 3 to 6 hours. This implies that the wind rose approach to drift predictions is highly inaccurate for phenomena lasting over 5 or 6 hours.

Table II.2.2
Average Persistence of Wind
Nantucket Island Airport &
Portland, Maine Airport

Wind Direction	Nantucket (Hours)	Portland (Hours)
N	6.2	3.9
NE	5.2	2.8
E	4.7	3.3
SE	4.6	2.1
S	5.5	4.8
SW	6.1	2.8
W	4.8	4.2
NW	4.3	3.2
CALM	1.7	2.9

(Seasonally averaged)

The technique we developed to handle this problem was to model the wind as a first-order Markov process. In this model we presume that the probability that the wind will change from one state to another is dependent only upon the characteristic of the wind at the moment of transition. In our present terminology the word state refers to some unique direction and speed range. Thus our Markov model would allow us to determine some measure of the probability that the wind will change from north at 10 knots (for example) to northwest at 17 knots. Various investigators have had considerable success in using these techniques when applied to other physical phenomena, and with the proper selection of "states" we can expect to develop a reasonable model for the wind.

We looked at several different possible state categorizations and rapidly came to the conclusion that we had best keep the number of states down to a manageable number even at the expense of compromising the assumed Markov property, simply because the amount of raw data required to generate the probabilities grows at least as fast as the number of states squared. Furthermore, it gets progressively more difficult to develop any kind of mental grasp of the process as the number of states increases.

The final selection we made was a simple nine-state system comprising N, NE, E, SE, S, SW, W, NW, and calm. The probabilities are contained in a nine by nine matrix, a sample of which is shown in Table II.2.3. The matrix is used as follows. One enters the matrix in the row corresponding to the wind direction at present. The numbers in the column elements of that row give the probability that the wind will be from the column's direction after 3 hours. The speed presumed for the wind is the average for that direction.

It turns out that this simulation of the wind has some inherent inaccuracies, the key one being that it doesn't account for the variability of the wind speed in a given direction range. However, the model was found to cause errors of only 10 to 20 percent, so it was retained. Future simulations should be modified to negate this problem. A thorough analysis is contained in Stewart (1973).

The two regions which we have investigated in detail are the Maine coast and Georges Bank. The winds along the Maine coast were presumed to be properly represented by those measured at the Portland, Maine Airport. The Georges Bank winds were assumed to be like those measured at Nantucket Island Airport. The first assumption seems reasonably well justified although the extreme northern edge of the Maine coast is about 150 nautical miles from Portland and we might expect some variation in the wind's behavior over this distance. The second assumption needs more support and fortunately this is available, at least from a wind rose standpoint. The Air Force operated two Texas Towers in the late fifties, one on Georges Bank and the other on Nantucket Shoals. The mean statistics (wind rose data) for the two are quite similar, the major difference being that the southwesterly appears to set in and displace the westerly at Nantucket about one month earlier than on Georges Bank. The average speeds are almost identical. Finally, the averages from Nantucket Shoals

Table II.2.3

Portland Airport: Autumn 3 Hourly Transition Matrix

	CALM	N	NE	E	SE	S	SW	W	NW
CALM	0.384	0.149	0.034	0.040	0.037	0.065	0.065	0.142	0.084
N	0.059	0.464	0.138	0.053	0.025	0.006	0.019	0.059	0.176
NE	0.031	0.340	0.340	0.170	0.062	0.005	0.010	0.031	0.010
E	0.066	0.056	0.112	0.391	0.157	0.168	0.010	0.020	0.020
SE	0.062	0.049	0.025	0.167	0.315	0.265	0.062	0.025	0.031
S	0.084	0.021	0.007	0.009	0.067	0.550	0.190	0.058	0.014
SW	0.099	0.029	0.019	0.003	0.019	0.178	0.363	0.261	0.029
W	0.104	0.060	0.012	0.012	0.012	0.044	0.129	0.504	0.124
NW	0.073	0.236	0.035	0.035	0.010	0.051	0.026	0.169	0.364

Wind Direction	Percent Observed	Mean Wind Speed	RMS	S	E
CALM	11.092	0.000	0.000	0.000	0.000
N	16.312	6.661	3.322	+0.994	0.909
NE	6.662	6.588	2.949	+0.920	0.842
E	6.765	6.670	2.739	+0.979	1.485
SE	5.563	7.093	3.812	+1.025	0.459
S	14.835	7.725	3.301	+0.535	0.130
SW	10.783	6.369	3.103	+0.998	0.983
W	17.239	7.092	3.786	+1.132	1.400
NW	10.749	6.629	3.782	+0.906	0.148

are very much like those collected at Nantucket Island. This completes the chain. Of course this doesn't really prove that their transition properties will be similar but it seems likely.

II.2.6 Simulation technique

In view of the foregoing discussion of the variability of the wind, and its importance in determining spill trajectories, we sought an analytic technique that would allow us to accomodate probabilistic behavior. The simplest and most straightforward appeared to be the use of Monte Carlo simulation. This simulation was based on the simple trajectory equation given earlier, with the current being treated as a non-random quantity which could be assigned direction and speed values as a function of location. The wind was modeled as the nine-state Markov process just discussed. The wind changed with the seasons, but the current remained fixed.

The broad outline of the computer program used to execute this technique is quite simple. A sample spill is released at a specified point. The initial wind direction is determined from steady state statistics. The spill's velocity is then computed and its progress is traced. Every simulated three hours the Markov matrix is entered and a new wind value is randomly selected according to the probabilities given by the matrix. The program also updates the current velocity and even the season as required as the spill moves from one location to the next, or from one season to the next. As the spill progresses on its trajectory, the computer keeps testing to see if the spill has either impacted land or washed out of the region of interest. Each sample spill is allowed to go for 150 simulated days before it is cast off and a new sample spill released. The process is repeated 200 times, that is, 200 sample realizations are made, for each season and launch point. The accuracy we can expect from such a process (if there were no inaccuracies in the input data) is on the order of plus or minus a few percent (1 to 6% depending on certain features of the problem) to a high degree of confidence. This could be reduced by running more than 200 sample realizations (say 1,000), but it was felt that other errors, particularly in the current specification, were so much greater that nothing significant was to be gained from the additional computational travail.

For situations where the spill was at sea for a long time (say over 20 days) before impacting land, no accounting was made of its spreading behavior. This was done because we believe that after this amount of time the spill will no longer be identifiable as a reasonably contiguoug slick, but rather it will appear as a region of tar balls and other oil remnants. Turbulent diffusion will tend to have spread the slick out beyond its contiguous area and meaningful predictions of the impact area can only be made with respect to long areas of shoreline, say 20 to 40 miles.

For shorter times, the spreading could be significant, and the treatment of the spill as a contiguous slick is fairly well justified. Therefore, for short times the radius of the slick was computed and the points of impact of the slick were determined using this radius.

II.2.7 Georges Bank spill

Chapter II.1 highlighted the hazard of spillage posed by an offshore oil development on Georges Bank. Several characteristics of a Georges Bank spill are of interest to us, including the length of time on the Bank, the probability of reaching shore as a function of location and the time to reach shore. In this section, we will concentrate on the probability of a Georges Bank spill reaching shore. Chapters II.5 and I.6 will use the results of the same analysis to address the problems posed by the spill while it is on the Bank.

Four hypothetical launch points were analyzed, each lying near the center of one of the four quadrants. They are shown in Figure II.2.4. For each of the 200 simulated spills emanating from each launch point in each season, the computer program computes time on the Bank; whether the spill hits land in any one of the following four regions:

1) South Coast: New England south of Provincetown, including Nantucket and Martha's Vineyard;
2) North Coast: New England coast north of the Cape and Cape Cod Bay;
3) Bay of Fundy: Bay of Fundy and western shore of Nova Scotia to Cape Sable;
4) Out of Region: Any other land;

and the time to hit shore.

We shall want to compare the results of these computations with the drift bottle data, which is summarized in Tables II.2.4 a, b, c, and d for each of the four launch areas and four recovery areas. Notice that the drift bottle results show a strong seasonal variation and also indicate that the Cape and South Coast region is the most likely area to recover a drift bottle released on Georges Bank. This strong seasonal behavior first pointed out the

Table II.2.4

% Recovered / Median Time to Shore

a) Winter

Recovery Region \ Launch Quadrant	NW	NE	SE	SW
South Coast	.3% / 150 d	.3% / 120 d	0% / -	0% / -
Mass-Maine Coast	.1% / 120 d	0% / -	0% / -	0% / -
Bay of Fundy	.1% / 150 d	0% / -	0% / -	0% / -
Out of Region	.3% / >180 d	.9% / >180 d	0% / -	.1% / >180 d

Spring

Recovery Region \ Launch Quadrant	NW	NE	SE	SW
South Coast	2.1% / 120 d	1.3% / 120 d	3.0% / 90 d	5.5% / 90 d
Mass-Maine Coast	.2% / 120 d	0% / -	0% / -	0% / 90 d
Bay of Fundy	.7% / 120 d	.8% / 120 d	.1% / 150 d	.2% / 150 d
Out of Region	1.0% / 180 d	2.1% / >180 d	2.9% / >180 d	2.2% / 150 d

Table II.2.4 (continued)

% Recovered / Median Time to Shore

c) Summer

Recovery Region \ Launch Quadrant	NW	NE	SE	SW
South Coast	.1% / 90 d	1.6% / 60 d	1.0% / 60 d	5.7% / 30 d
Mass-Maine Coast	0% / -	0% / -	0% / -	.1% / >180 d
Bay of Fundy	.1% / 90 d	.5% / 150 d	0% / -	.2% / 90 d
Out of Region	.7% / 120 d	1.3% / 90 d	1.8% / 120 d	3.9% / 90 d

d) Spring

Recovery Region \ Launch Quadrant	NW	NE	SE	SW
South Coast	0% / 90 d	0% / >180 d	0% / -	.1% / 60 d
Mass-Maine Coast	0% / -	0% / -	0% / -	0% / -
Bay of Fundy	0% / 120 d	0% / -	0% / -	.1% / 90 d
Out of Region	.1% / >180 d	.1% / >180 d	0% / -	0% / -

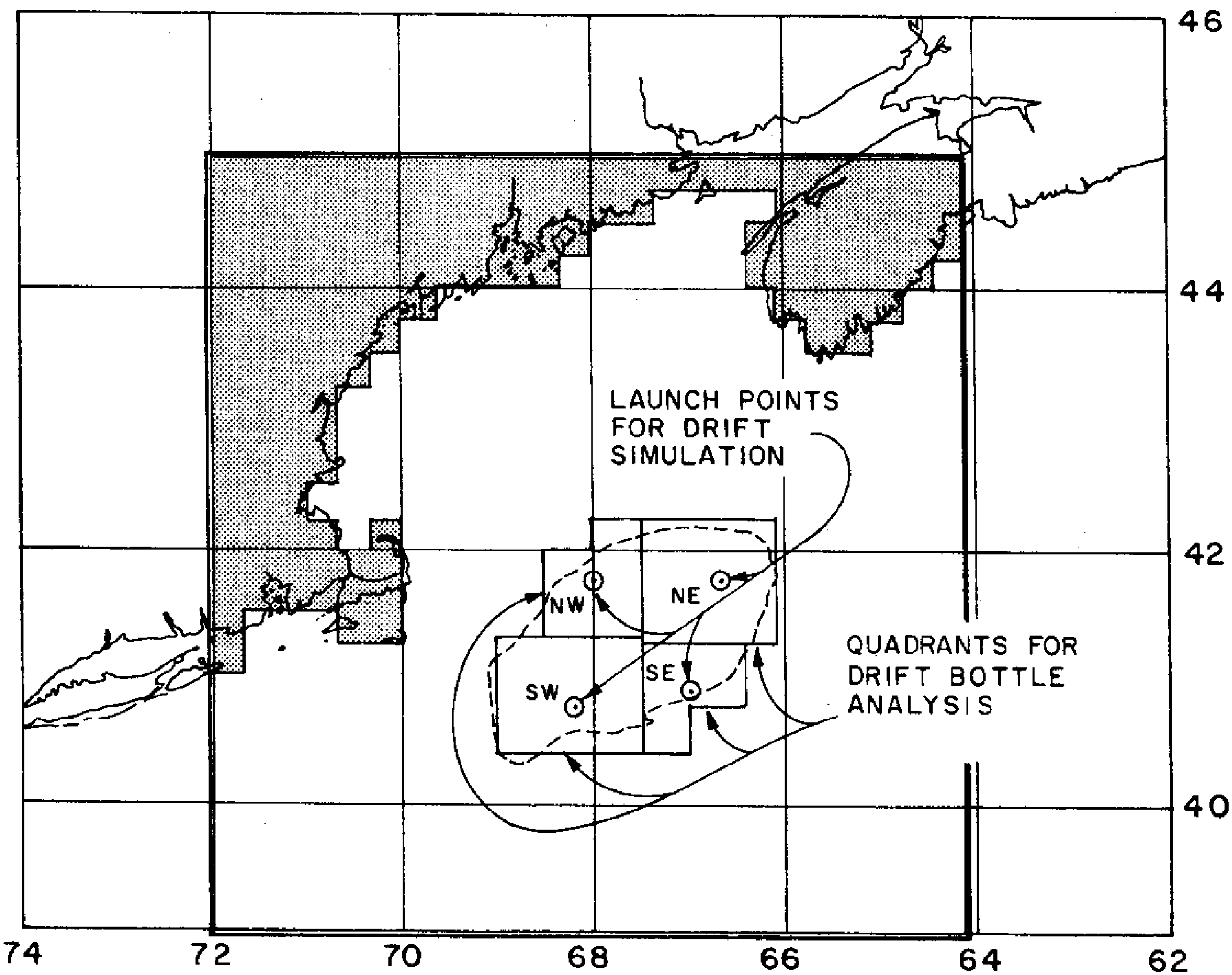


FIGURE II-2-4 OUTLINE OF NEW ENGLAND USED IN COMPUTER SIMULATION shortcoming of the wind rose statistics, because the wind rose changed much less dramatically with the season. One problem in interpreting this data is that the bottles were not released uniformly over the quadrants but rather tended to group along the more common track lines of oceanographic vessels doing station work. This caused, for example, a fair number of the bottles released from the SW quadrant to be released from the common northerly track at 69°W longitude (Great South Channel). This may account for some of the high percentages observed from the SW quadrant.

For the purposes of the computer program, the broad outline of the New England region was approximated with square blocks 15 miles on a side. The total region covered was a square with 360 nautical miles on a side. Figure II.2.4 shows the basic grid work. The wind was presumed to be like that on Nantucket Island over the whole region. Any spill crossing into the cross-hatched regions was counted as having hit shore. A separate tally was maintained for each region of interest.

A total of four different geostrophic current patterns were investigated:

a) No Current: the no current case was tried for two possible values of the wind drift coefficient, 1.5% and 3%. The fall and winter returns to shore were unaffected as they both were zero for all launch points. The spring and summer returns were out of line with our drift bottle data, with the 3% wind drift giving us the worst fit. The principal problem was far too many returns to the Bay of Fundy and no returns to the Cape Cod region. The 3% wind drift gave an overall return ratio for the Bay of Fundy of 15% for all of Georges Bank, while the 1.5% wind drift figure gave a 6% return ratio. It was felt the discrepancy was due to a very poor current assumption and that the results had little bearing on the selection of the wind drift coefficient. This pattern was tested primarily to give us a baseline for comparing subsequent current patterns.

b) Current Pattern No. 1 (see Figure II.2.5): this pattern retained a large region centered over the northern edge of Georges Bank in which there was no current, but added southwesterly current along the Massachusetts-Maine coast; a southerly current down South Channel; a southwesterly current just outside of Georges Bank; a north-easterly current well offshore, and a strong current around the tip of Nova Scotia and up into the Bay of Fundy. This is an approximation of the generally accepted circulation. However, it also resulted in far more returns to the Bay of Fundy than have ever been observed. In addition, it appeared that a few percent of the trajectories heading toward the Bay of Fundy were now entrained by the southwesterly current on the north side of Georges Bank and they eventually impacted the Massachusetts-Maine shore or Cape Cod.

c) Current Pattern No. 2 (see Figure II.2.6): this pattern was very similar to No. 1 with the exception that the bottles going to the Bay of Fundy were now forced to traverse 20 to 40 miles of opposing southwesterly current just to the north of Georges Bank. Additionally, the south-westerly current off the Connecticut-Rhode Island shore was replaced by a westerly current. A remarkable thing happened: no bottles got to the Bay of Fundy. In fact, returns to shore were nil for all seasons, and the computer

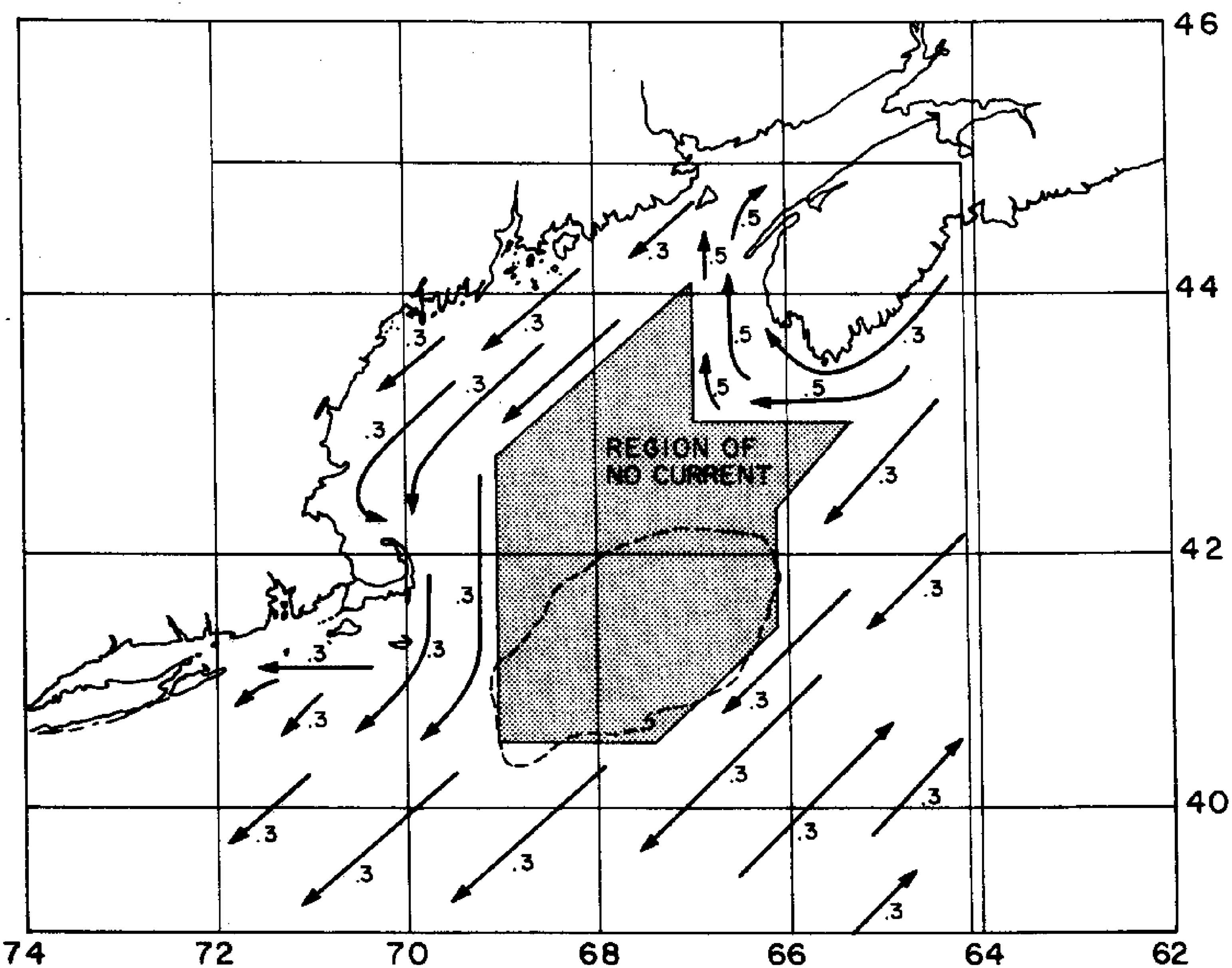


FIGURE II-2-5 CURRENT PATTERN NO. I

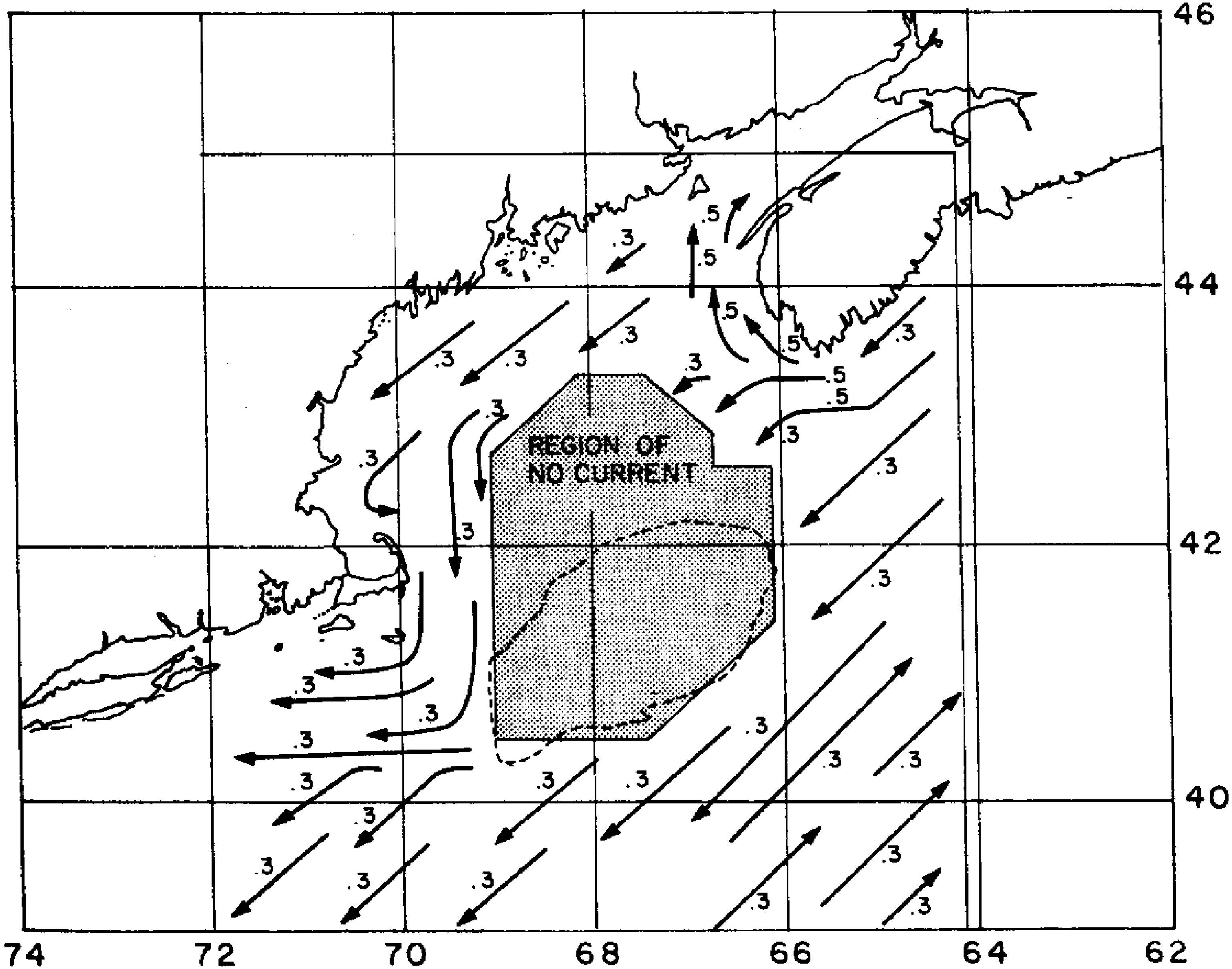


FIGURE II-2-6 CURRENT PATTERN NO. 2

indicated that in the summer launching a substantial fraction had been left in transit after 150 days at sea without ever going out of the region or washing ashore. This implied that a fair number were trapped in the northern portion of the presumed no-current area.

d) Current Pattern No. 3 (see Figure II.2.7): this current pattern deviated from No. 2 in that the large no-current region was assigned a gentle southwesterly flow at .1 knots; the southerly flow through South Channel was slowed to .1 knot. These results showed the qualitative behavior of the drift bottles by season, and the magnitudes even roughly agree with the drift bottle results. A detailed summary of these results is contained in Figures II.2.8 through II.2.11.

Some of the pertinent characteristics for this pattern are as follows:

1) minimum time to shore = 31 days (The limited sample size reduces our confidence that this is a true minimum. A more accurate statement is that this was the minimum value observed in the 10 to 15 realizations that hit shore.)
2) average time to shore = 68 days
3) average time on Georges Bank = 36 days

The above data is averaged over all of Georges Bank for spring and summer (there were virtually no returns for fall and winter). More detailed information is available through the computer printout, if desired.

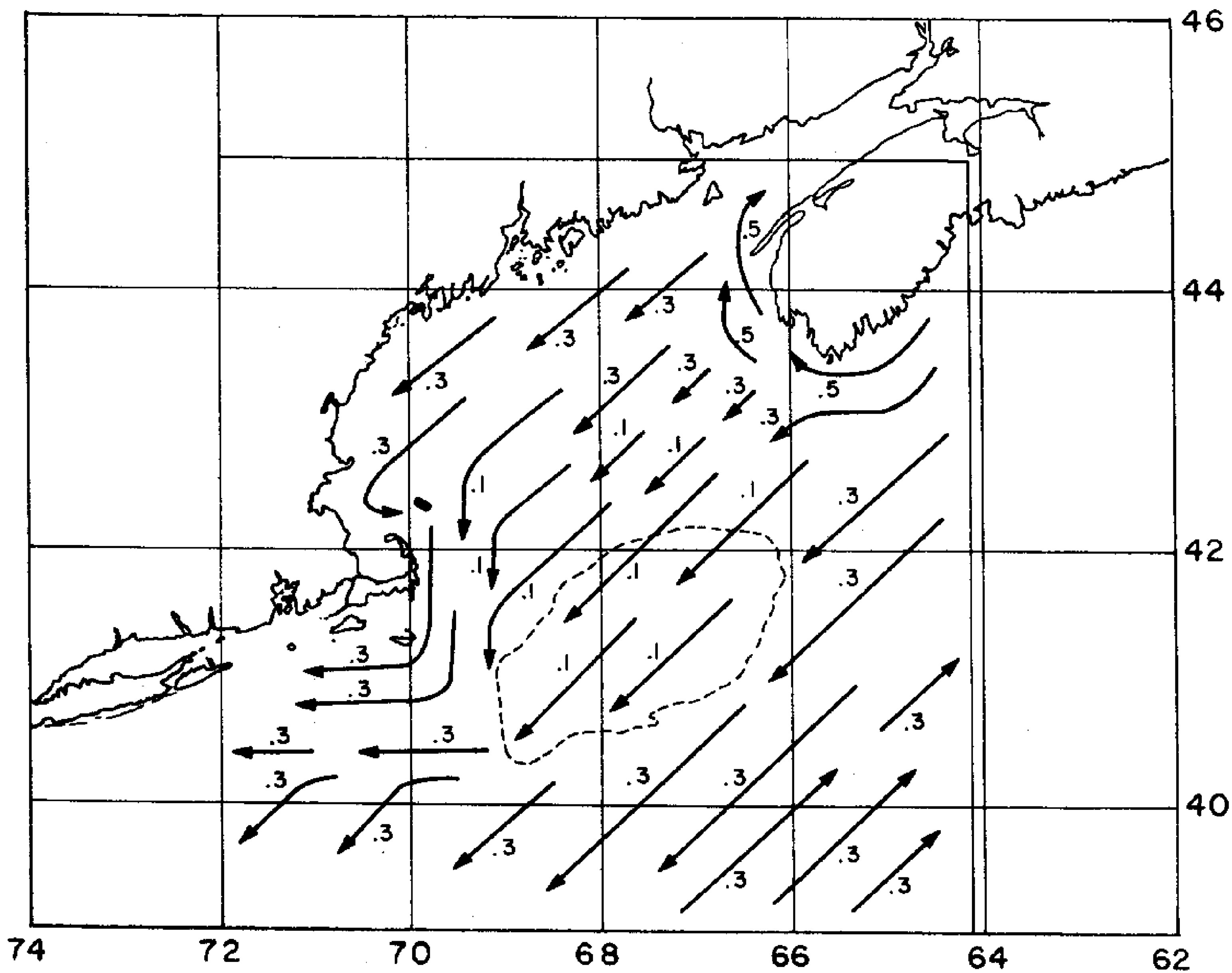


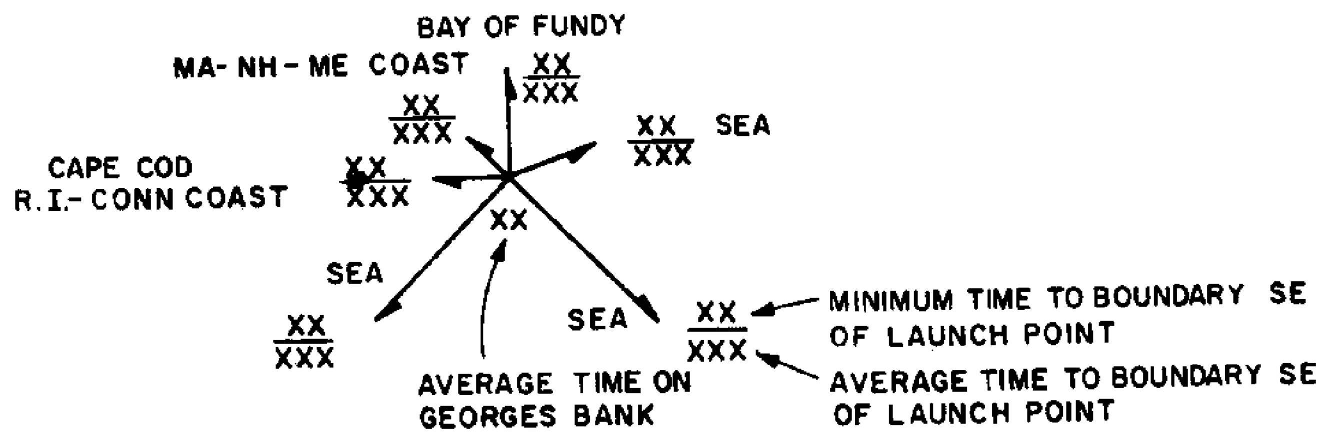
FIGURE II-2-7 CURRENT PATTERN NO. 3

EXPLANATION OF SYMBOLS FOR FIGURE II-2-8 THRU II-2-11

1. ARROW INDICATES PERCENT TRAJECTORIES TERMINATING IN REGION ARROW POINTS TO, SCALE INDICATED ON DRAWING.

2. FRACTIONAL NUMBER AT TIPS OF ARROWS INDICATE $= \left\{ \frac{\text{MINIMUM TIME TO REGION}}{\text{AVERAGE TIME TO REGION}} \right\}$ IN DAYS.

3. NUMBER DIRECTLY BELOW LAUNCH POINT INDICATES AVERAGE TIME SPENT BY SPILL ON THE WATERS OVER GEORGES BANK, IN DAYS.



4. IF THERE ARE NO FRACTIONAL NUMBERS, THEN NO TRAJECTORIES TERMINATED IN THAT DIRECTION.

5. THE DRIFT BOTTLE DATA IS SUMMARIZED SIMILARLY, THE TIME AT SEA IS NOT A WELL SUBSTANTIATED NUMBER SO ONLY THE MEDIAN TIME IS INDICATED.

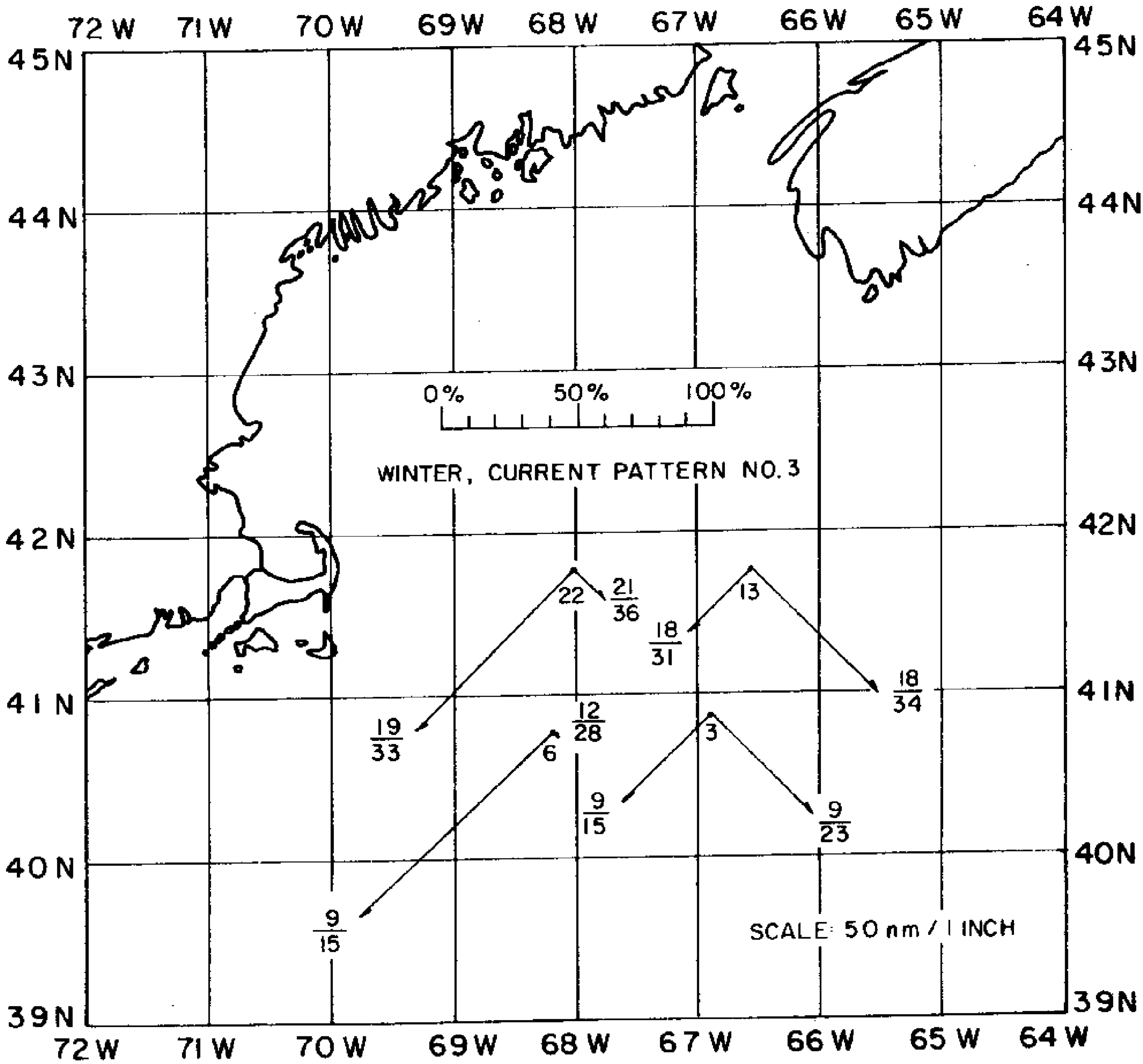


FIGURE II-2-8a SUMMARY OF TRAJECTORY PROBABILITIES

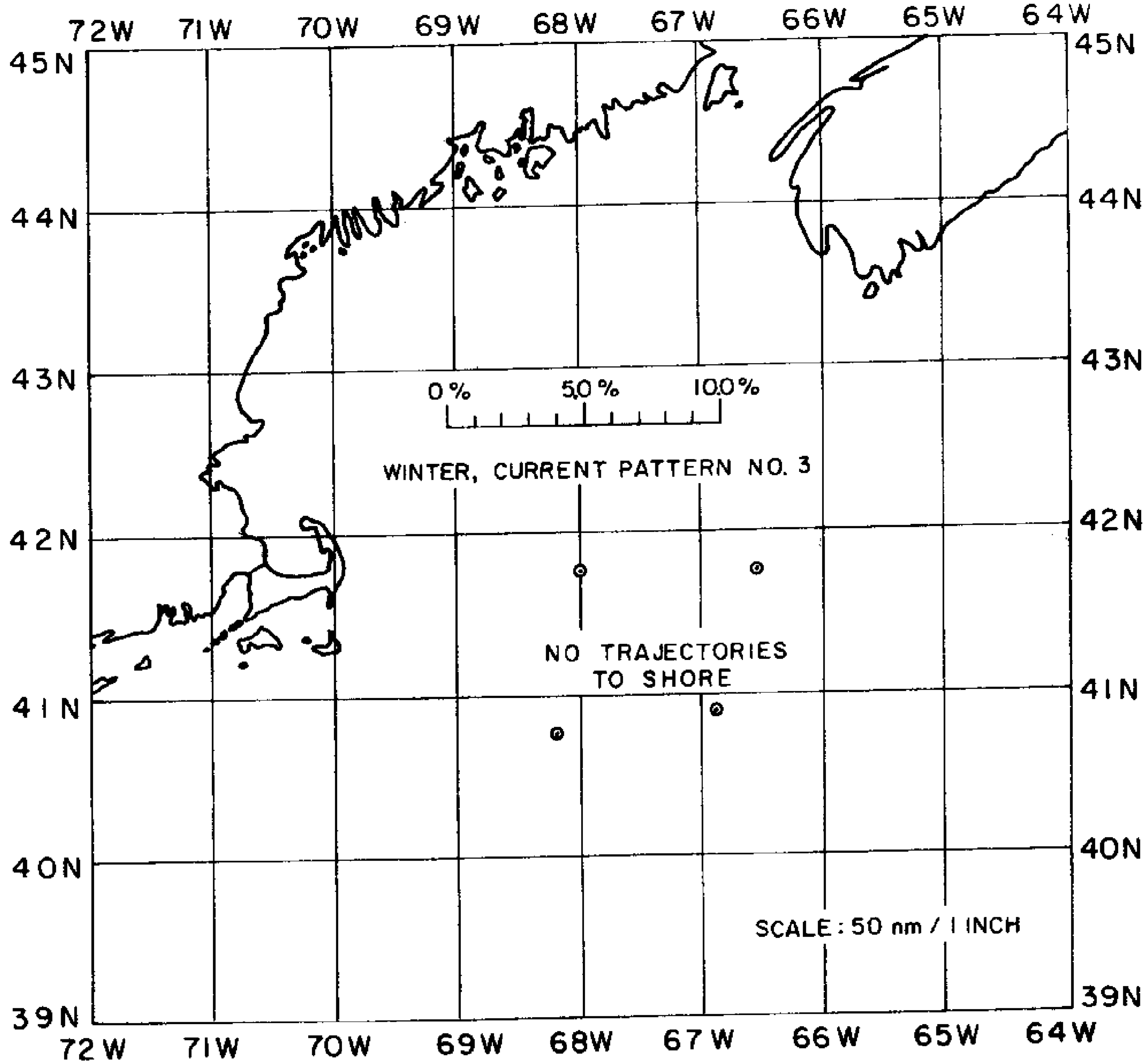


FIGURE II-2-8b EXPANDED SCALE SUMMARY OF TRAJECTORIES TERMINATING ON NEW ENGLAND OR BAY OF FUNDY SHORE

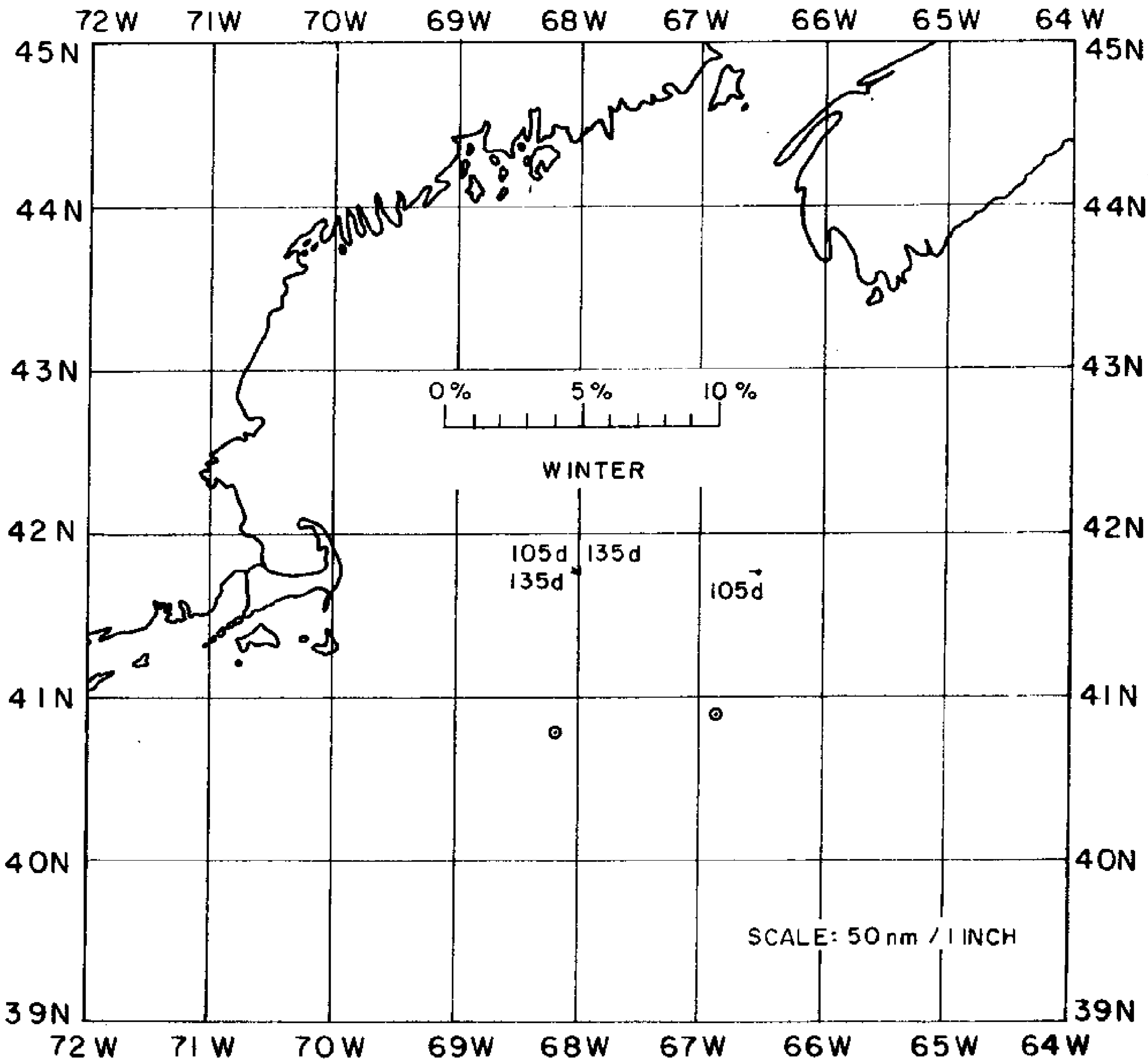


FIGURE II-2-8c EXPANDED SCALE SUMMARY OF DRIFT BOTTLE RETURNS TO NEW ENGLAND AND BAY OF FUNDY SHORES

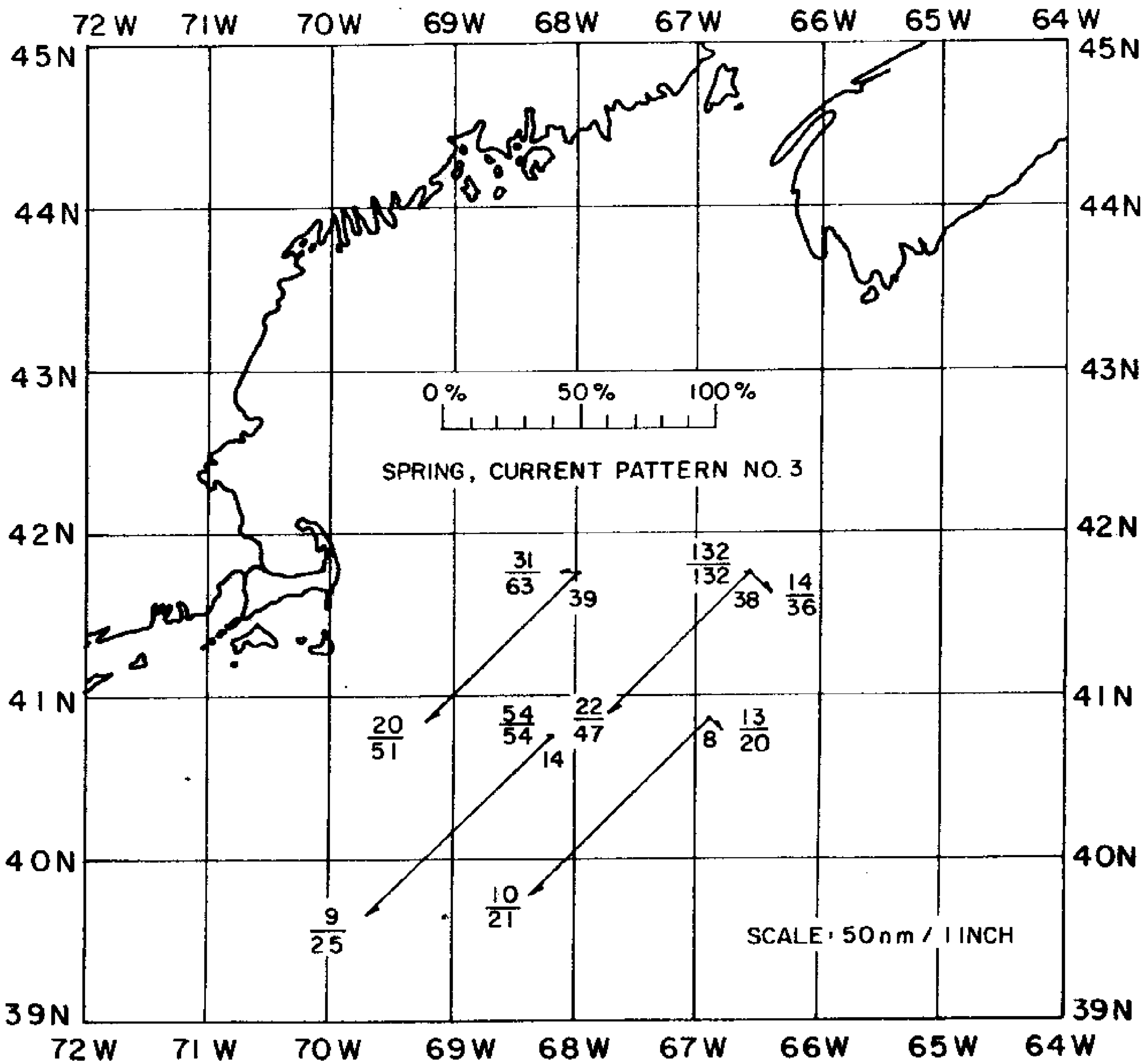


FIGURE II-2-9a SUMMARY OF TRAJECTORY PROBABILITIES

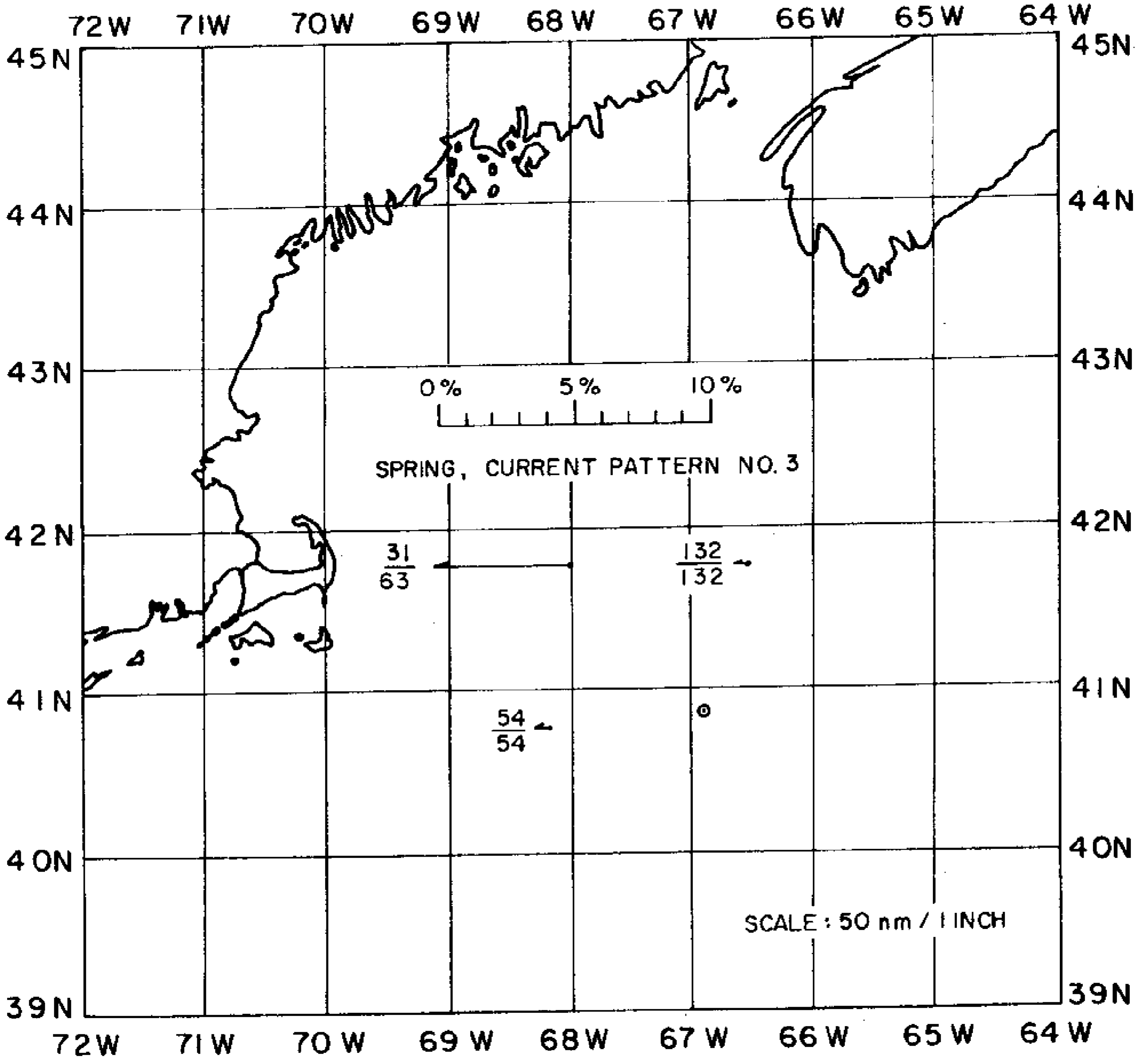


FIGURE II-2-9b EXPANDED SCALE SUMMARY OF TRAJECTORIES TERMINATING ON NEW ENGLAND OR BAY OF FUNDY SHORES

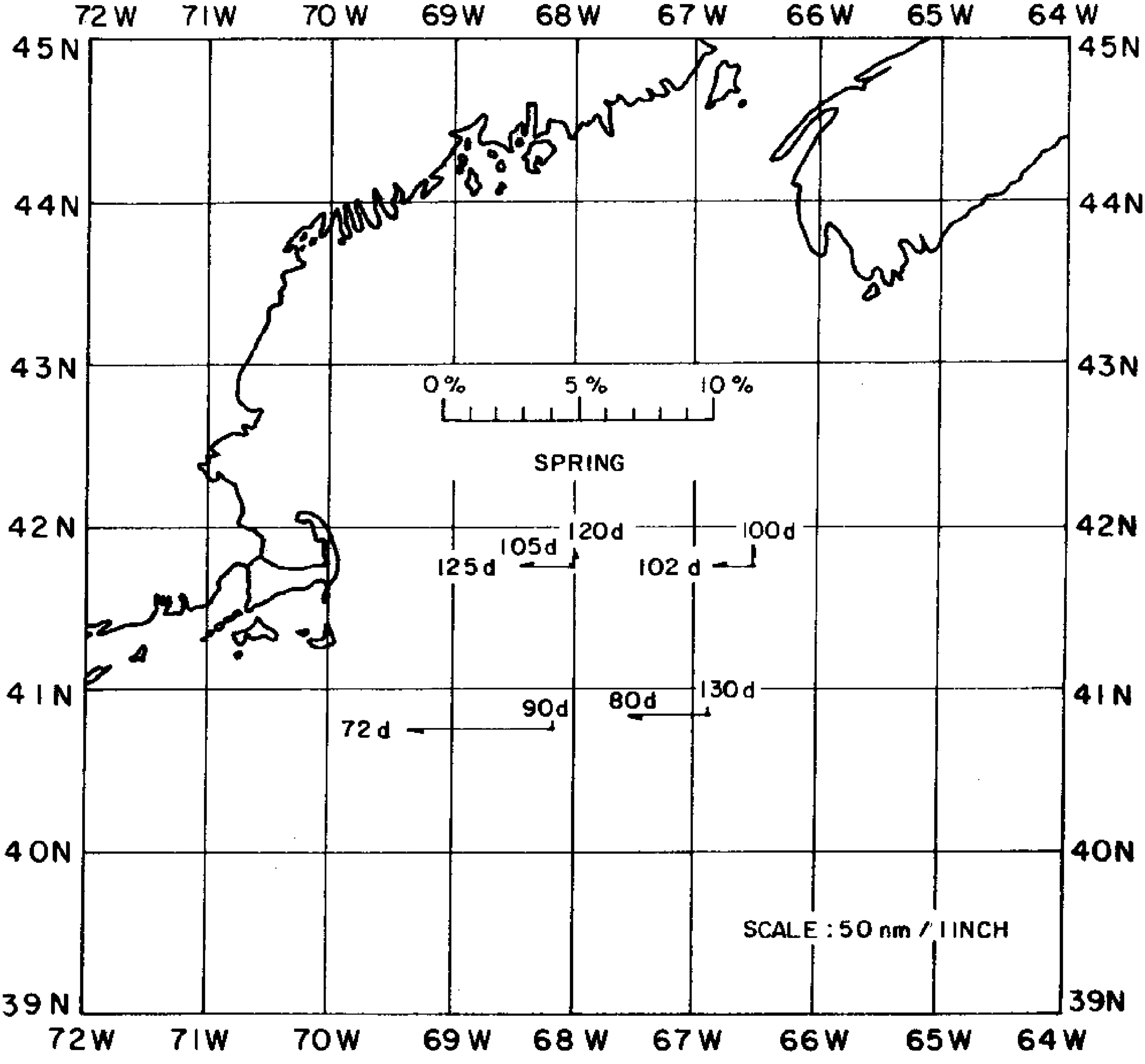


FIGURE II-2-9c EXPANDED SCALE SUMMARY OF DRIFT BOTTLE RETURNS TO NEW ENGLAND AND BAY OF FUNDY SHORES

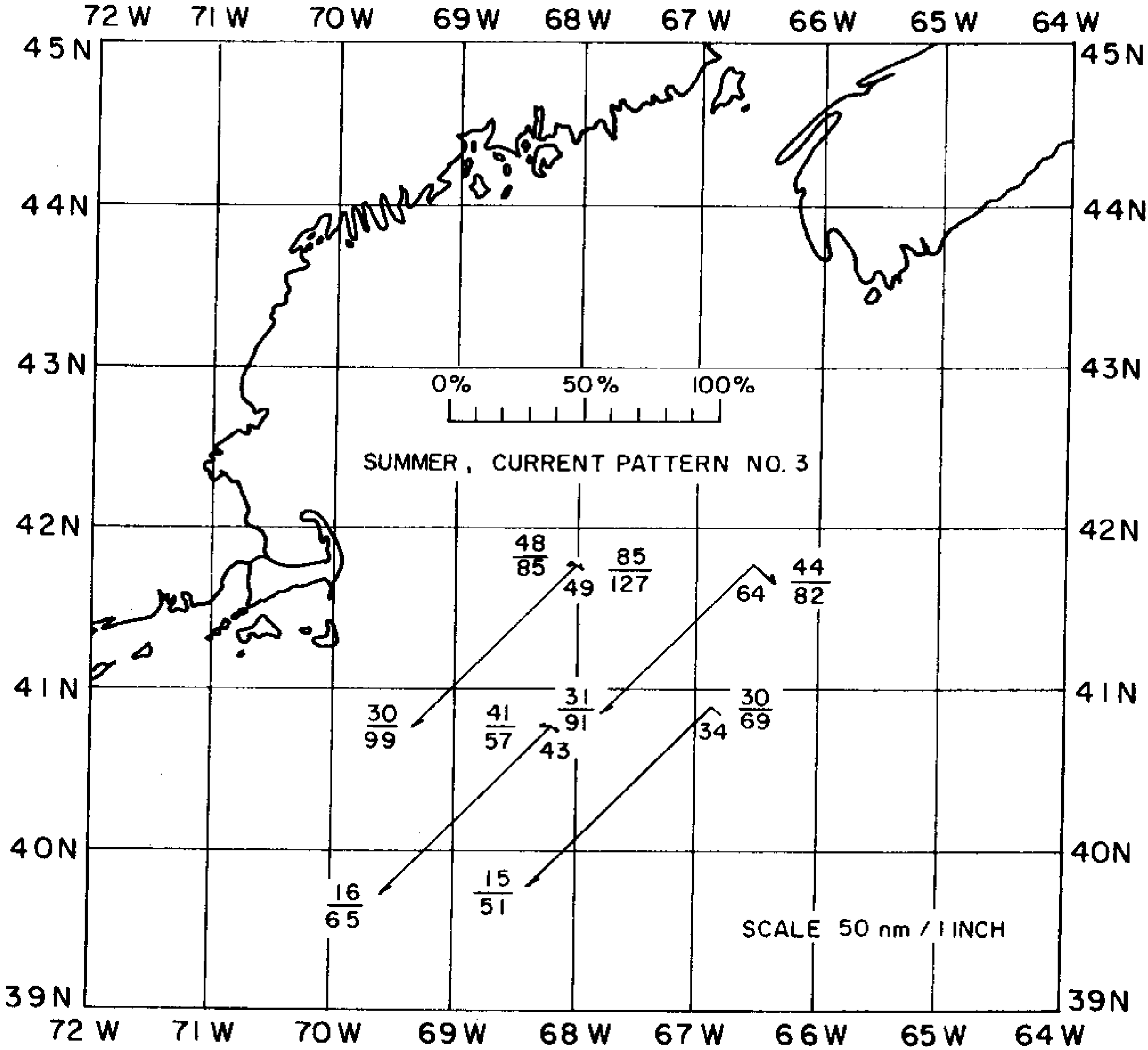


FIGURE II-2-10a SUMMARY OF TRAJECTORY PROBABILITIES

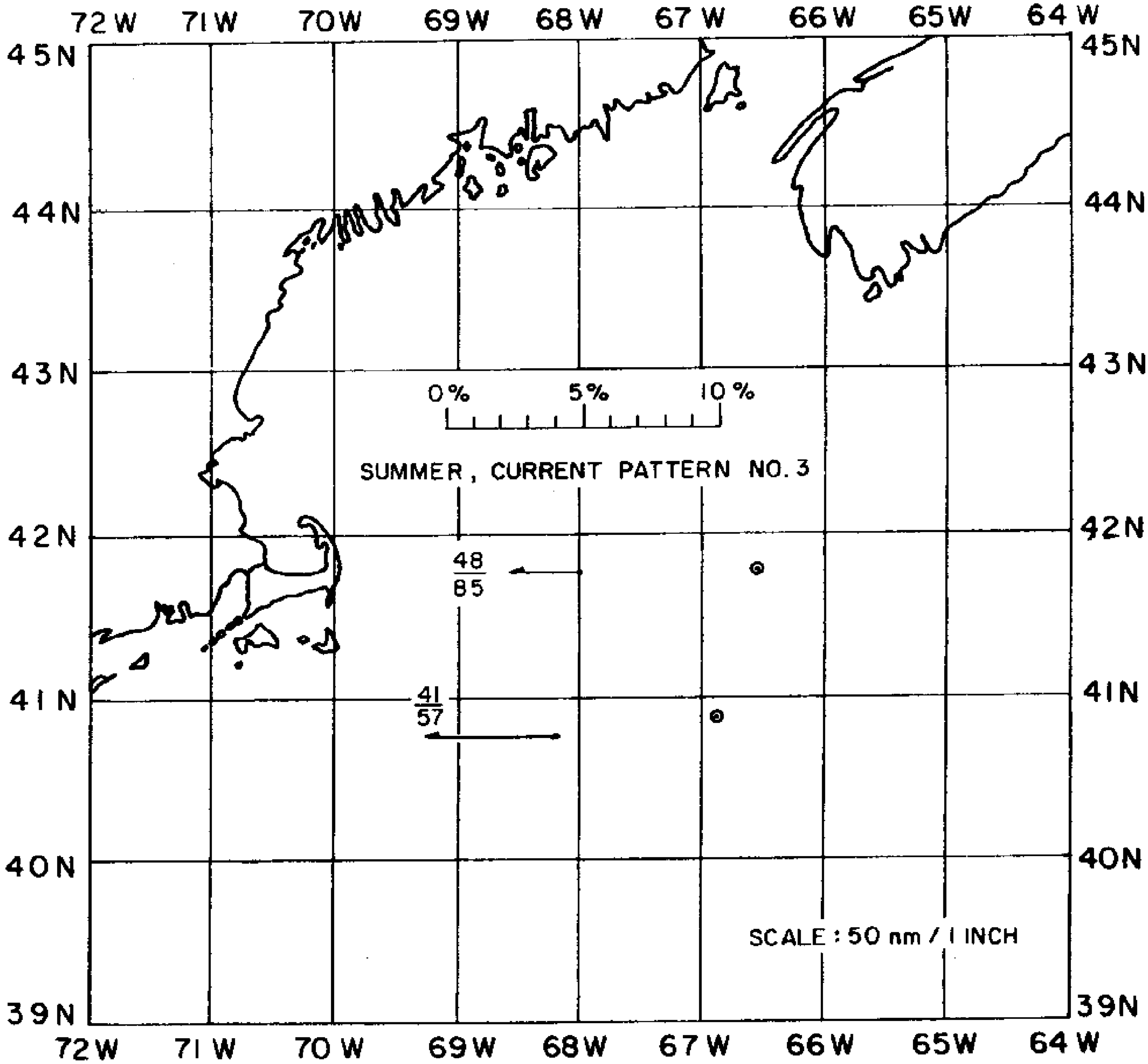


FIGURE II-2-10b EXPANDED SCALE SUMMARY OF TRAJECTORIES TERMINATING ON NEW ENGLAND OR BAY OF FUNDY SHORES

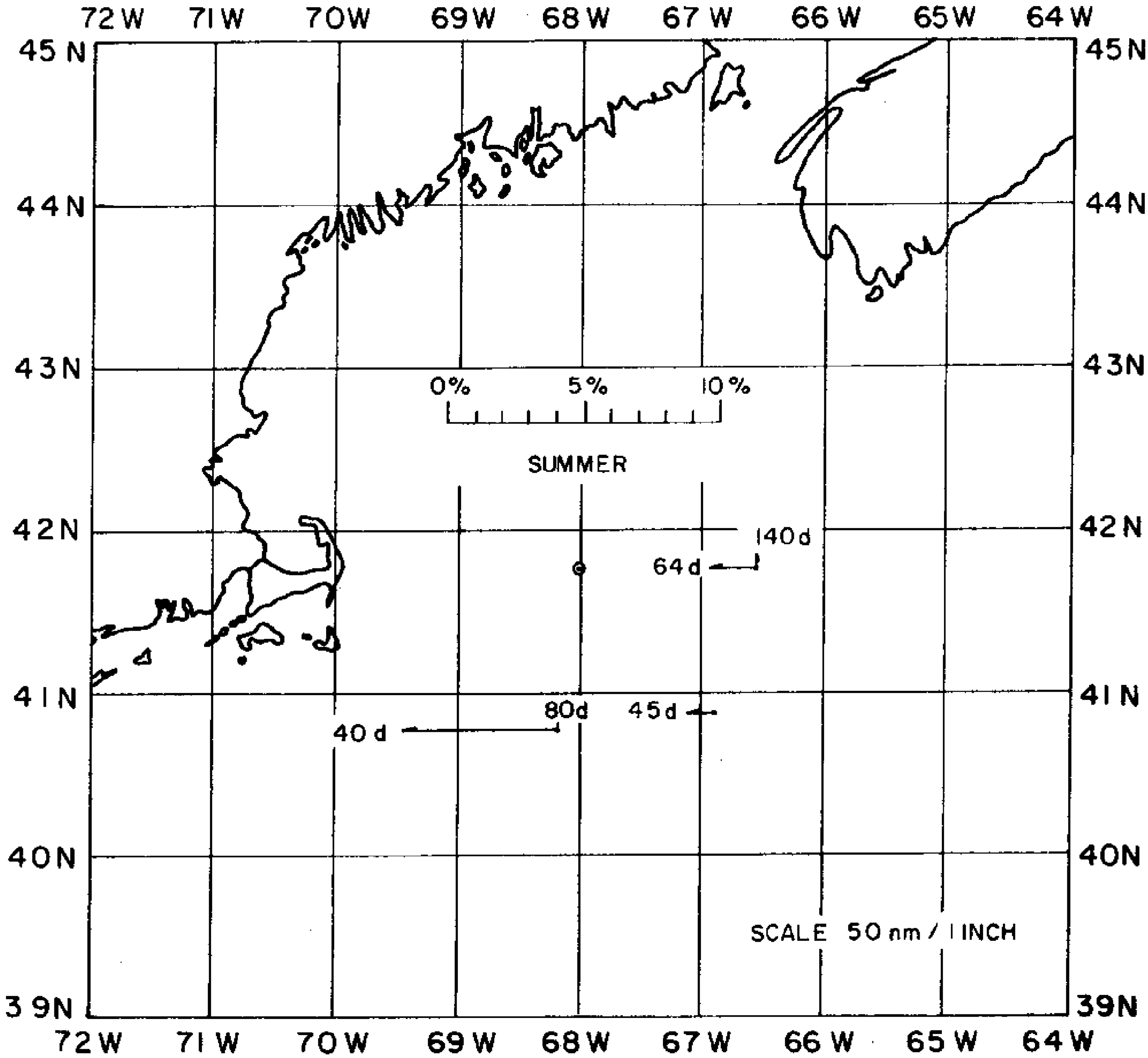


FIGURE II-2-10c EXPANDED SCALE SUMMARY OF DRIFT BOTTLE RETURNS TO THE NEW ENGLAND AND BAY OF FUNDY SHORES

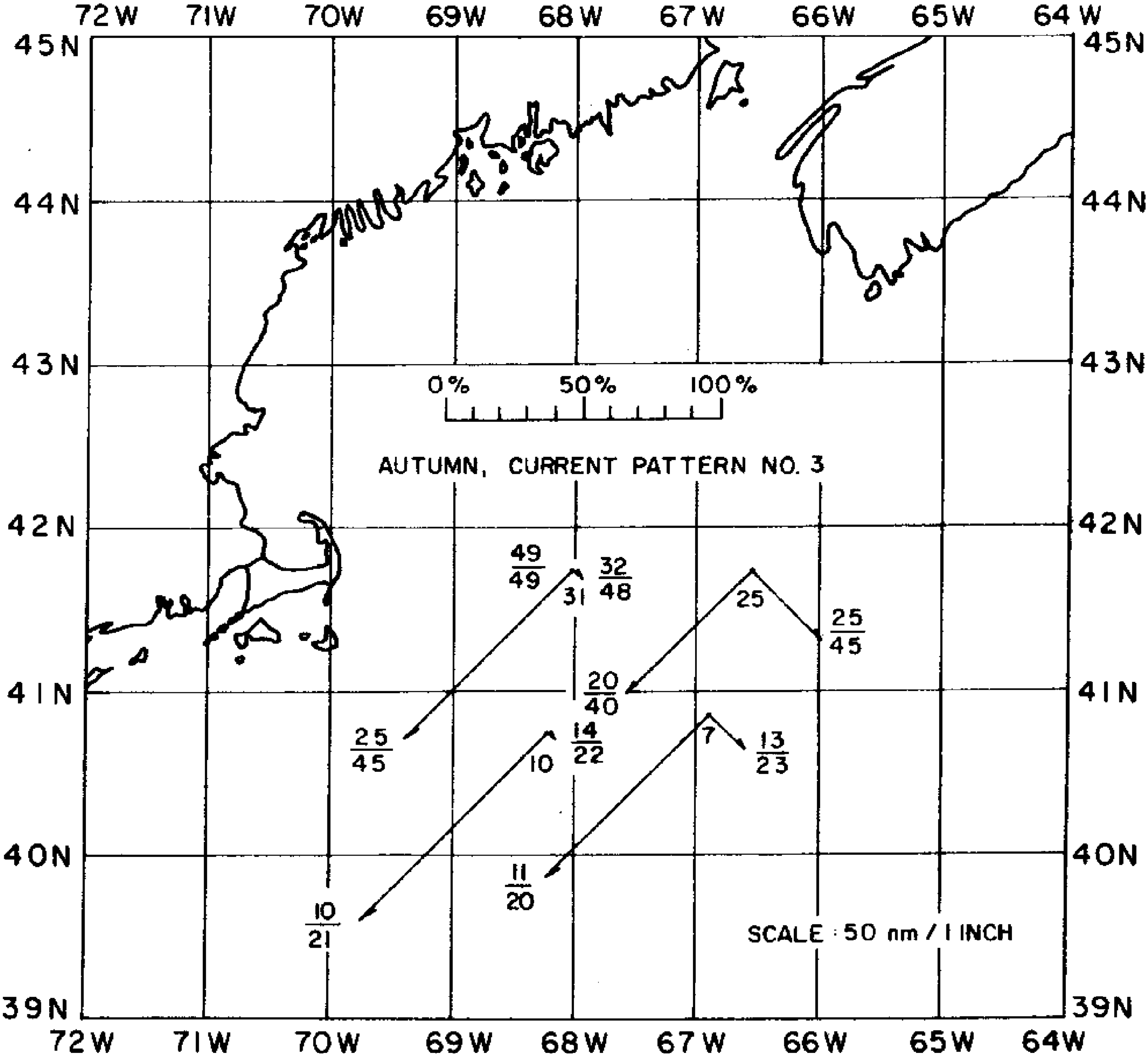


FIGURE II-2-11a SUMMARY OF TRAJECTORY PROBABILITIES

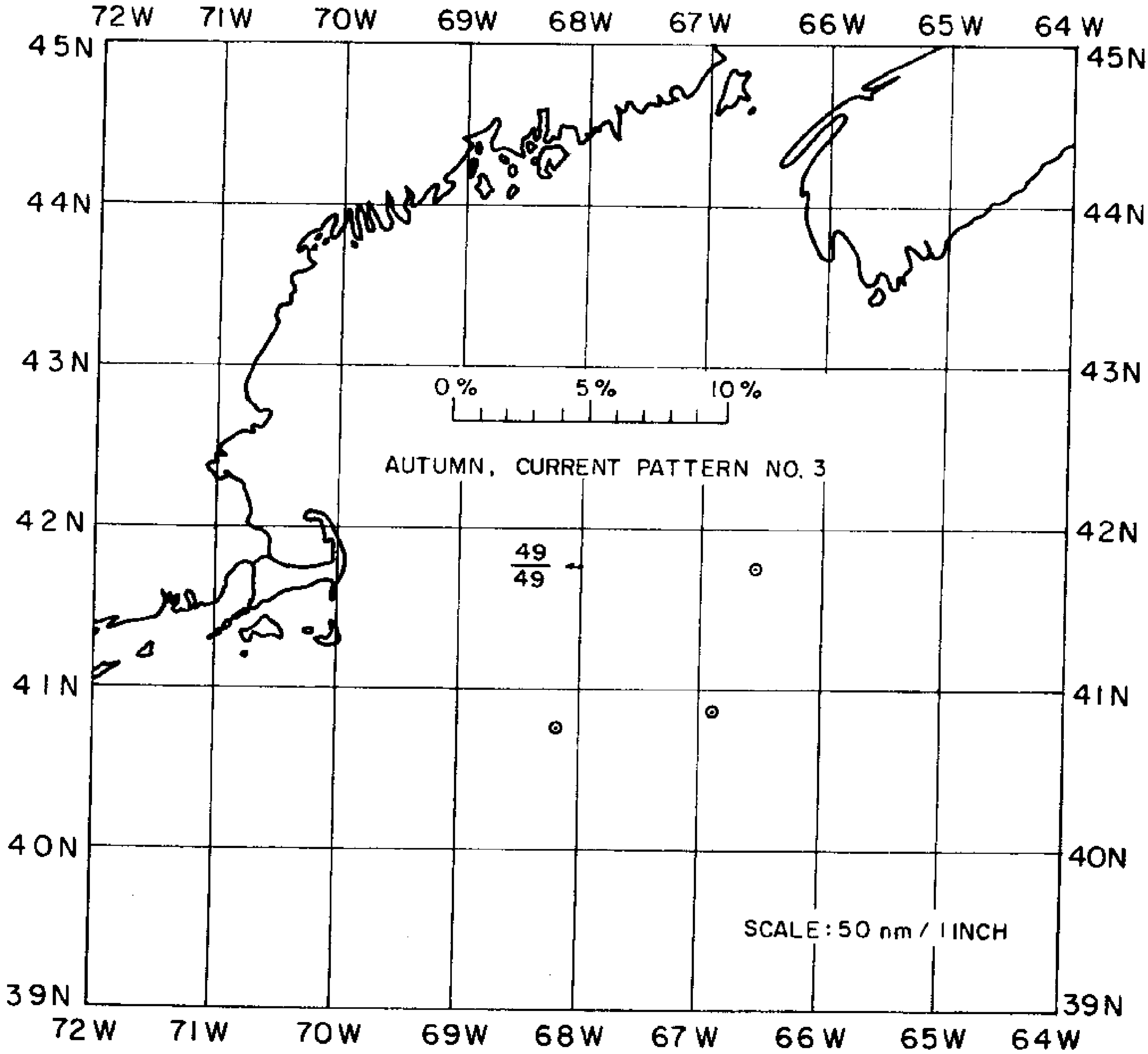


FIGURE II-2-11b EXPANDED SCALE SUMMARY OF TRAJECTORIES TERMINATING ON NEW ENGLAND OR BAY OF FUNDY SHORES

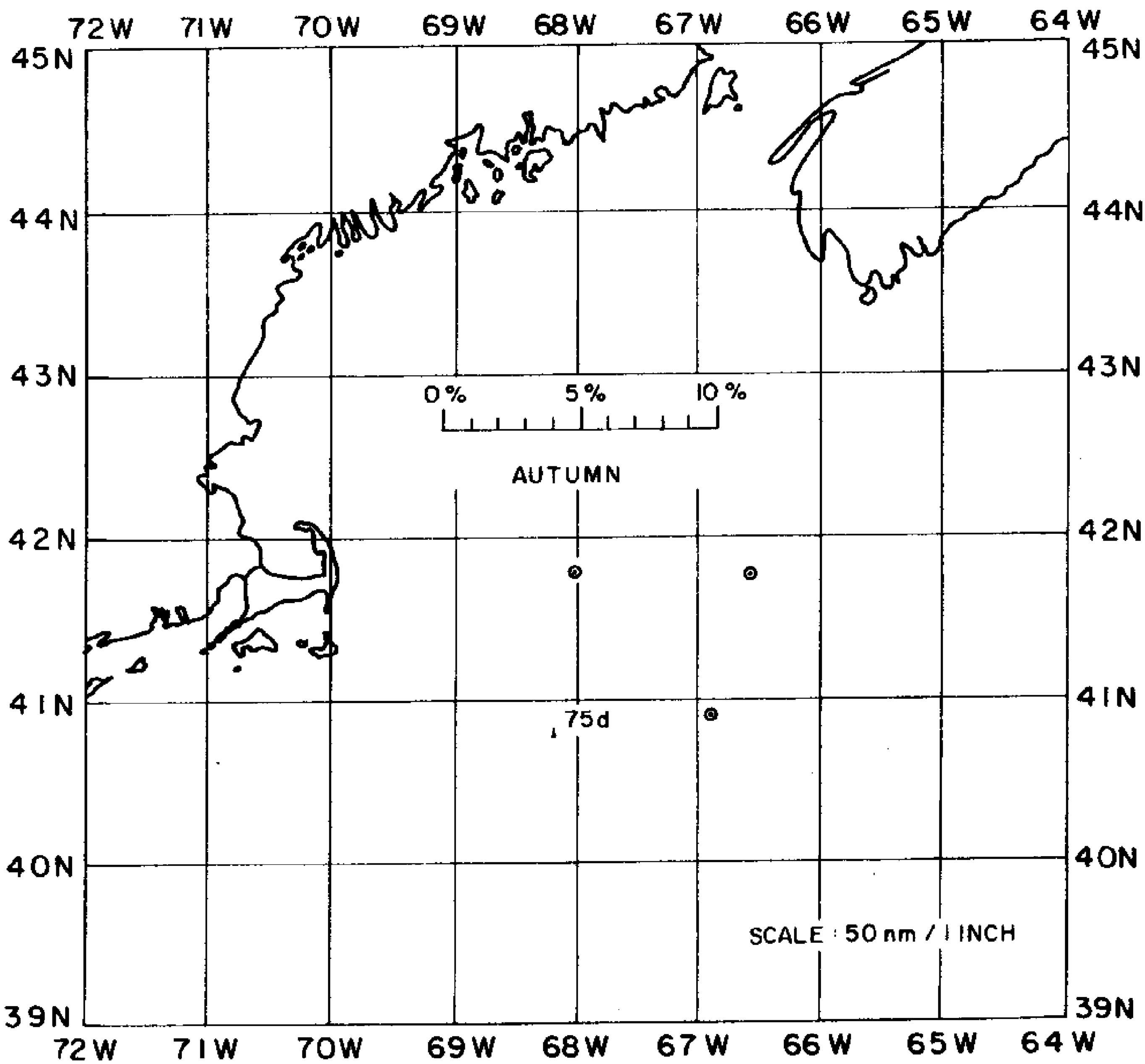


FIGURE II-2-11c EXPANDED SCALE SUMMARY OF DRIFT BOTTLE RETURNS TO THE NEW ENGLAND AND BAY OF FUNDY SHORES

Current Pattern No. 3, then, has some rather attractive properties. It is in general agreement with the commonly held views of the circulation in the Gulf of Maine and it is quite consistent with the drift bottle results. The problem with accepting these results at face value is that we are almost certain that Pattern No. 3 is not a unique solution to the current pattern problem. Further, we cannot justify the selection of Pattern No. 3 over No. 2 or any other generally similar pattern based on any data independent of the drift bottle returns.

Despite this uncertainty, there are certain statements that can be made:

1) The probability of a Georges Bank spill coming ashore in New England is highly variable, varying from nil in the winter to as high as 5% in the summer. The northwesterly component of the winter winds makes it extremely difficult for any cold season Georges Bank spill to reach shore under a wide range of possible current patterns.

2) Any spill reaching shore will take at least 30 days to reach shore and will probably require 60 days.

3) Under current assumptions consistent with the drift bottle data, almost all the spills which come ashore in New England will do so on the western and southern shore of Cape Cod.

4) The key impact of our uncertainty regarding current pattern is on the Bay of Fundy area. Rather minor changes in the current pattern can increase the number of spills reaching the Bay of Fundy during spring and summer from 0% to 10%. Under those current and season assumptions which yield the high rate of return to the Bay of

Fundy, 1-2% of the spills will reach the northern New England coast.

It is important that some long-term statistics be acquired for the spring and summer currents on Georges Bank and in the region lying just north and west of Georges Bank. As we saw in the discussion of Current Pattern No. 3, the inclusion of just a very gentle southwesterly current made a substantial difference in the outcome with respect to Cape Cod. Similarly, if the possibility of polluting Canadian waters is important, then some current surveys must be made to determine if the currents in the Gulf of Maine are ever very close to zero knots, or worse yet, in a northerly direction. This could be a very substantial issue, because the percent returns to the Bay of Fundy become quite large in these two cases in the spring and summer seasons.

We emphasize that long-term data may be required because the currents in the Gulf of Maine will be determined by such things as the spring runoff into the Gulf of St. Lawrence, as well as the runoff into the waters of the Gulf of Maine. Meanders of the Gulf Stream could become very important, and even long-term climatogical trends may be significant.

There is some reason to be fairly optimistic about this situation, because Mr. Bumpus and Mr. Foster Stiffler of WHOI have developed a free-drifting, telemetering buoy suitable for long-term current measurements. They hope to start actual field measurements this next summer.

II.2.8 Nearshore spill, Maine coast

As we mentioned in an earlier section, the nearshore spill is in a region in which the tidal current plays an important role. In fact, in harbors or bays having high peak tidal currents, the major portion of the transport process will be by tidal current alone. This presents serious problems from an analytical standpoint because the variations in tidal current velocity from one point to the next could cause distortion and even separation of the slick surface. For example, consider a slick several miles across being washed directly onto an island within a bay. The current will flow around the island, dividing the slick into two parts (as well as coating the island's beaches). As this process is repeated over and over we end up with more and more individual patches. As the number of patches increases the number of beachings increases and soon the whole problem blows up, in part because of the difficulty in accounting for the oil stranded in beaching or refloated in a rising tide. The prevailing winds will have some influence in the trajectory, but since only three percent of the wind's velocity applies to the slick's motion, it takes some very strong (and very unlikely) winds to even approach the effect of a one or two knot tidal current.

Superceding the above arguments is the fact that we just don't know the tidal currents for any of the bays or harbors in Maine (with the exception of a few tidal velocities reported for isolated passes or points). Thus, analysis within a Maine Coast harbor or bay is completely infeasible.

Qualitatively, we can extrapolate from the "Tamano" spill in Casco Bay and say that any spill whose final area is at least one-tenth and perhaps one-hundredth the area of the bay in which the spill occurs is going to pose a very real threat to all the beaches on the bay. Any proposal to locate a terminal facility must simply accept this as a fact of life and make preparations accordingly.

A problem that does yield to analysis is just how local is the hazard posed by a specific terminal location. That is, is a terminal in Machias Bay a problem that only affects the people of northern Maine, or can Portland waters also be affected by a Machias spill? The problem fits into our methodology because we can construct the boundaries in such a way that the areas of strong tidal current are excluded from the problem. We will simply assume that once a spill gets into waters with strong tidal currents then the spill is washed about sufficiently to coat the beaches in that immediate area.

Figure II.2.12 shows one possible geometry that allows the use of this sort of assumption. As we shall later be interested in determining whether locating the facility further offshore is of benefit from a spill hazard standpoint, four possible launch points were considered. They lie 1, 2, 4, and 8 nautical miles off the idealized shoreline. The average current off the Maine coast is not known, but it seems probable that it will lie between zero knots and perhaps 0.3 knots, SW. We explored a variety of current patterns within this range to determine the variation in transport behavior caused by the current.

The whole point in formulating our problem in terms of the idealized shoreline was to allow us to neglect the specifics of the oil's behavior. Unfortunately, we must now cope with these specifics, at least in some generalized sense, because the amount of oil retained by the coastal regions within our idealized shoreline will determine the amount of oil left for further transport down the coast. We can postulate two extremes of behavior. On the one hand, the transport distance will be minimized if all the oil that crosses into the tidal region is absorbed on the beaches of that region. This presumption neglects secondary relaunchings of the spill and further presumes that

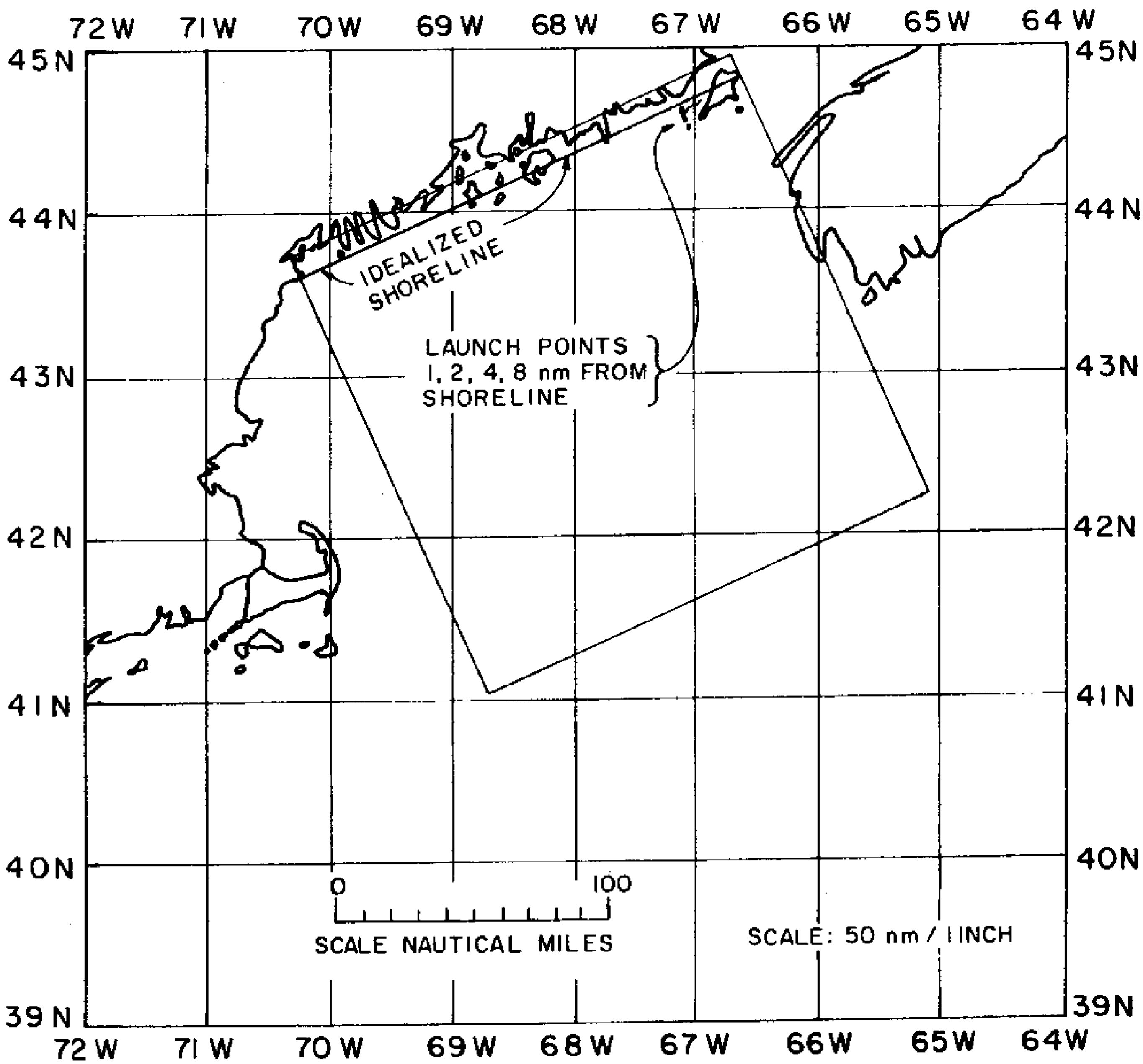


FIGURE II-2-12 NEARSHORE SPILL MODEL

all the oil will hit a beach or other absorbing obstacle, rather than just wash in with the tide and then wash back out. This behavior might be considered "best" case, because it will tend to cause the spill to be limited to a much more localized region.*

A "worst" case behavior can be constructed by presuming that none of the spill is absorbed upon crossing into the tidal region, but rather, it is just stored in that position until the winds and current are favorable for another trip up or down the coast or out to sea. This worst-case behavior can be considered to mimic at least the transport of the remnants of a spill long after it has ceased to be a large contiguous mass. An actual spill would tend to fall in between the two extremes, possibly lying closer to the latter than to the former.

This analysis was carried out for a one million gallon spill from each of the four launch points, for each season. Figures II.2.13 through II.2.15 summarize the results for the launch point one mile offshore. Figure II.2.13 shows the seasonal probabilities that a 1.8 nautical mile length of shore will be touched at least once given a spill occurred one mile off the idealized coastline at Machias Bay, presuming that the coast is non-absorbing. This represents the "worst" case result, or alternatively, the extent to which remnants might travel down the coast. No current and a very slight SW current were found to cause the widest variation in behavior. The 0.3 knot SW current was less influential in generating undesirable results because its offshore component was strong enough to cause the spills to be washed out to sea, except for a very particular wind pattern.

It is speculative, of course, to presume that the current is slightly offshore rather than parallel to it,

*Biologically, this might be a "worst" case, so remember that "best" here refers only to the localization of the spill.

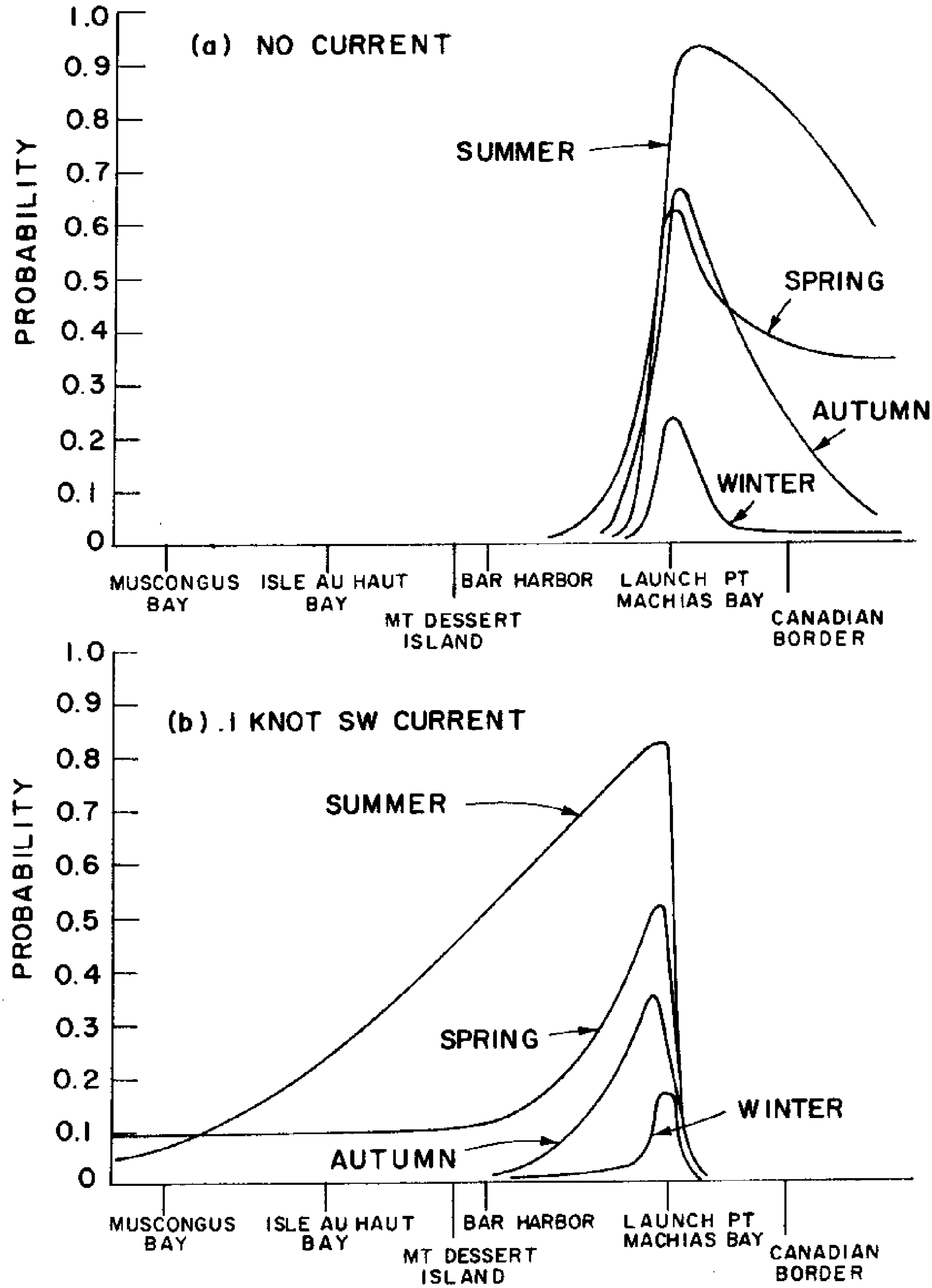


FIGURE II-2-13 PROBABILITY THAT A 1.8 nm LENGTH OF SHORE IS TOUCHED ONCE DURING LIFE OF SPILL. NON-ABSORBING, IDEALIZED SHORELINE; 1 MILLION GALLON SPILL; LAUNCH POINT 1 nm OFF IDEALIZED COAST.

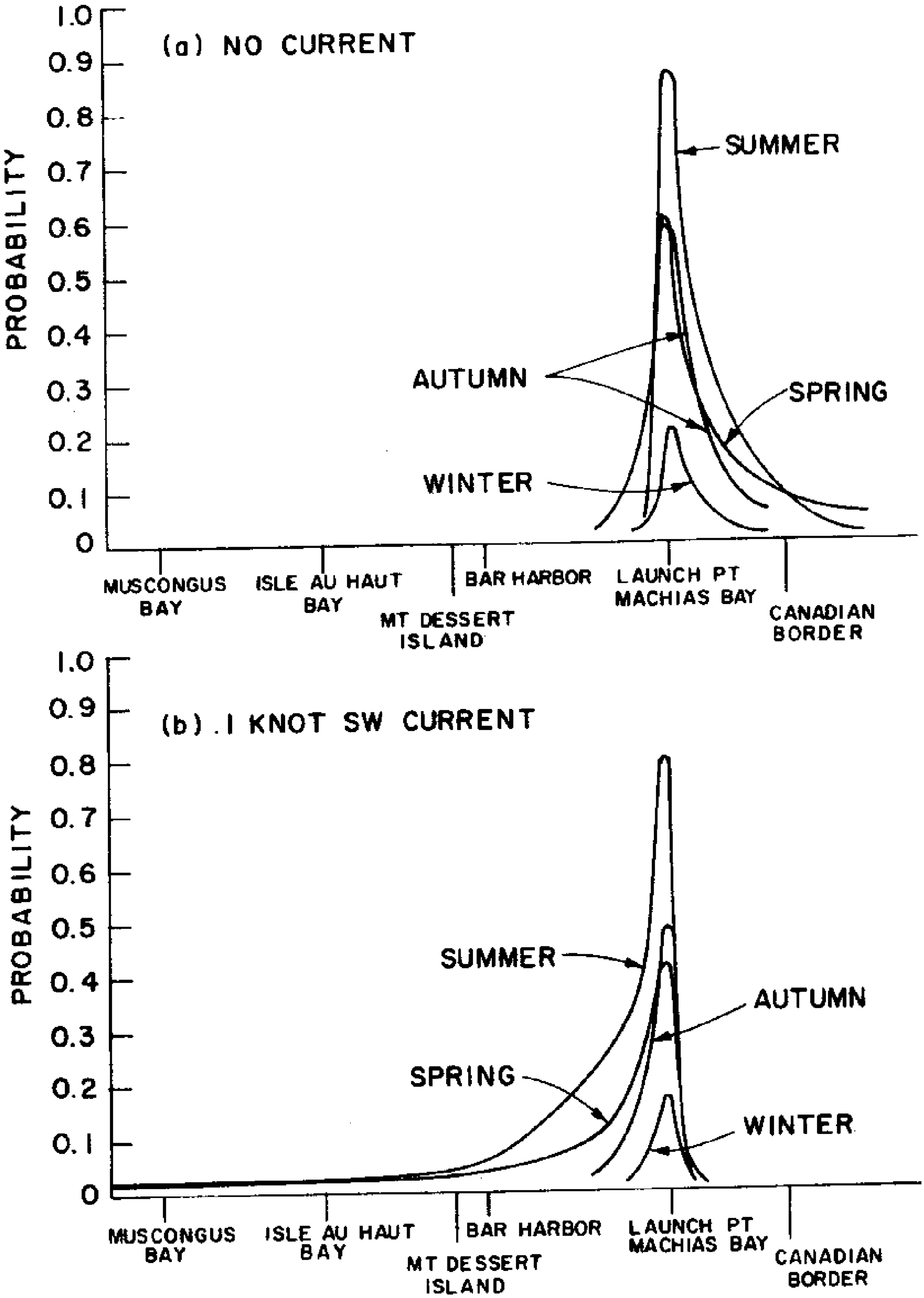


FIGURE II-2-14 PROBABILITY THAT A 1.8 nm LENGTH OF SHORE IS TOUCHED ONCE DURING LIFE OF SPILL. ABSORBING, IDEALIZED SHORELINE; 1 MILLION GALLON SPILL; LAUNCH POINT 1 nm OFF IDEALIZED COAST

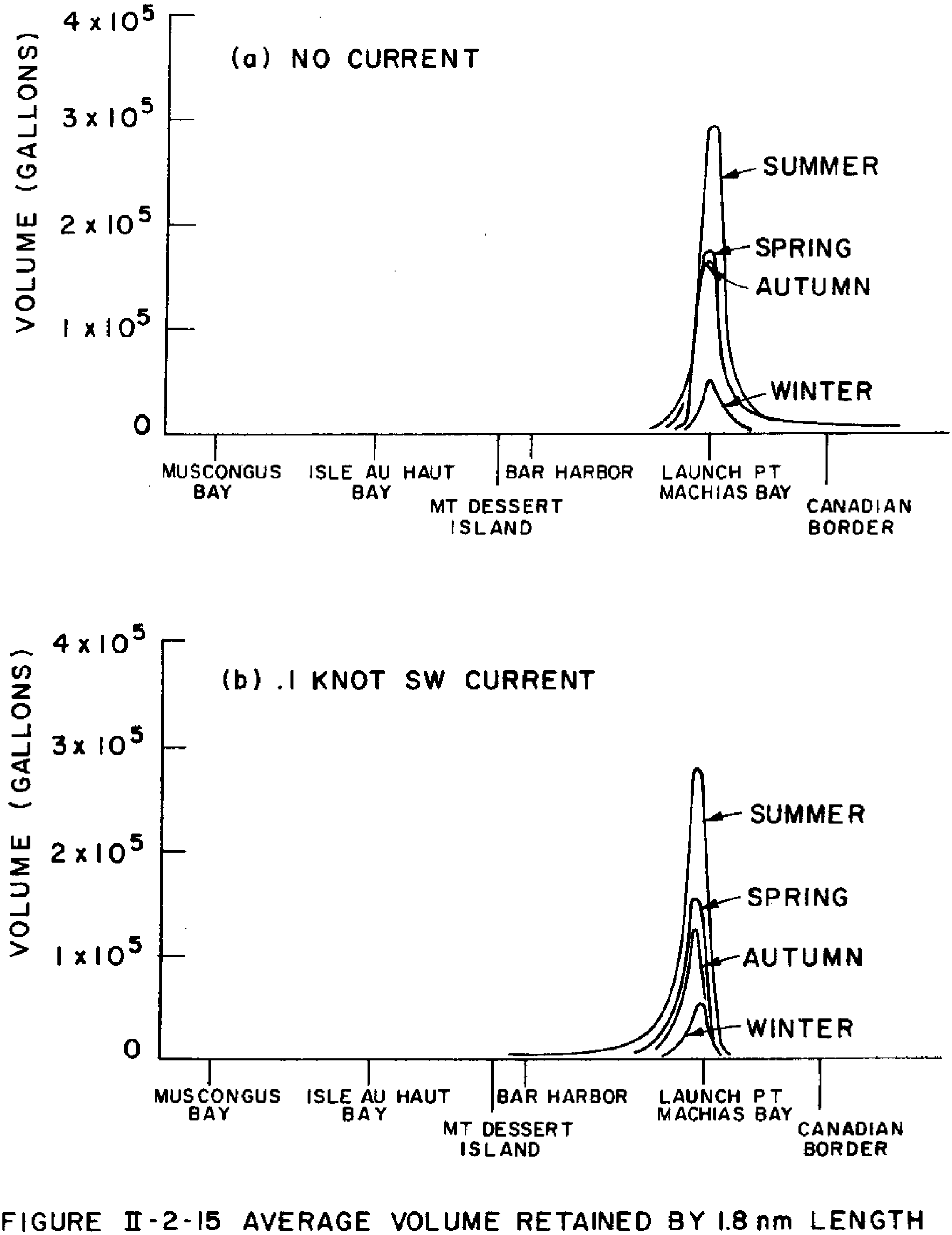


FIGURE II-2-15 AVERAGE VOLUME RETAINED BY 1.8 nm LENGTH OF SHORE PER 1 MILLION SPILL (INCLUDES ALL SPILLS, THOSE THAT GO ASHORE, AND THOSE THAT DON'T). ABSORBING, IDEALIZED SHORELINE; LAUCH PT. 1 nm OFF IDEALIZED COAST but one of the main driving forces would seem to come from the surface runoff of fresh water from the various rivers emptying into the Gulf of Maine, and this should cause a net outward motion. This observation is reinforced by sea bed drifter experiments (Graham, 1970) in which it was shown that the bottom waters of the Gulf of Maine lying near the Maine coast are drawn up into major estuaries to replace water that was apparently entrained by the overlying fresh water and then carried out to sea. The alongshore component of the sea bed drifters' trajectory was usually in a northeast to southwest direction, substantiating our basic presumption.

Figure II.2.14 shows the results from the "best" case (absorbing) analysis. Again, the parameters displayed are the chance that a 1.8 mile length of idealized shoreline will be touched at least once versus location along the coast. Figure II.2.15 displays the average volume of oil that would be absorbed by the absorbing shoreline along a 1.8 mile length, as a function of its position.

The main conclusions to be drawn from these graphs are that once again the current behavior is crucial in specifying the basic drift of the spill; once again, the phenomenon is highly seasonal; and finally, while the probability of finding remnants of an oil spill is .2 or more all the way from Penobscot Bay to the Canadian border during summer, the average volume per spill deposited on an absorbing shoreline in a spill incident is highly localized about the launch point.

The average volume figure is somewhat misleading as it includes both spills that come ashore and those that don't. It is the average amount of oil we would expect to collect every 1 million gallon spill incident after observing many incidents along a 1.8 mile length of shore. Another figure of interest, therefore, is the amount of oil deposited on a 1.8 mile length of shore counting only those spills that go ashore. This data is presented in Figure II.2.16. The curves tailing to the left or right of the launch point should be regarded as being highly uncertain due to the small number of realizations available for the mean value computation, and due to certain artifacts caused by the deterministic transition step size presumed in our model of the wind transport. The data is sufficiently accurate, however, to make the generalization that near the launch point, a 1.8 mile length of shoreline can expect to receive approximately 3×10^5 gallons from a 1 million gallon spill, given the spill goes ashore. As we get more than seven or eight miles away from the launch point, this value drops to less than 1×10^5 gallons per 1.8 miles of shoreline, and is probably in the range of 3×10^4 gallons to 5×10^4 gallons. It must be remembered also that we have presumed that all the oil that crosses the idealized shoreline is retained. In practice, this assumption is probably much too optimistic. It seems certain that if the oil is not removed through some cleanup activity, then a substantial fraction will be left for further transport up or down the coast. This implies that our estimates are merely lower bounds. No technique for estimating an upper bound (short of the total volume spilled) seems feasible.

Another topic of some interest is what are the trade-offs involved with an offshore, single-point moor versus an onshore, inner tidal terminal. Utilizing the four launch points, the percentage of spills that washed ashore was computed for each season. This computation was done considering only the motion of the center of mass of the spill. The criterion used was once the center of mass passed within the idealized shoreline, then that spill was counted as going ashore. The results of this analysis are shown in Figure II.2.17. Note that if there is a .3 knot southwesterly current, then locating the mooring point further out greatly diminishes the probability that the center

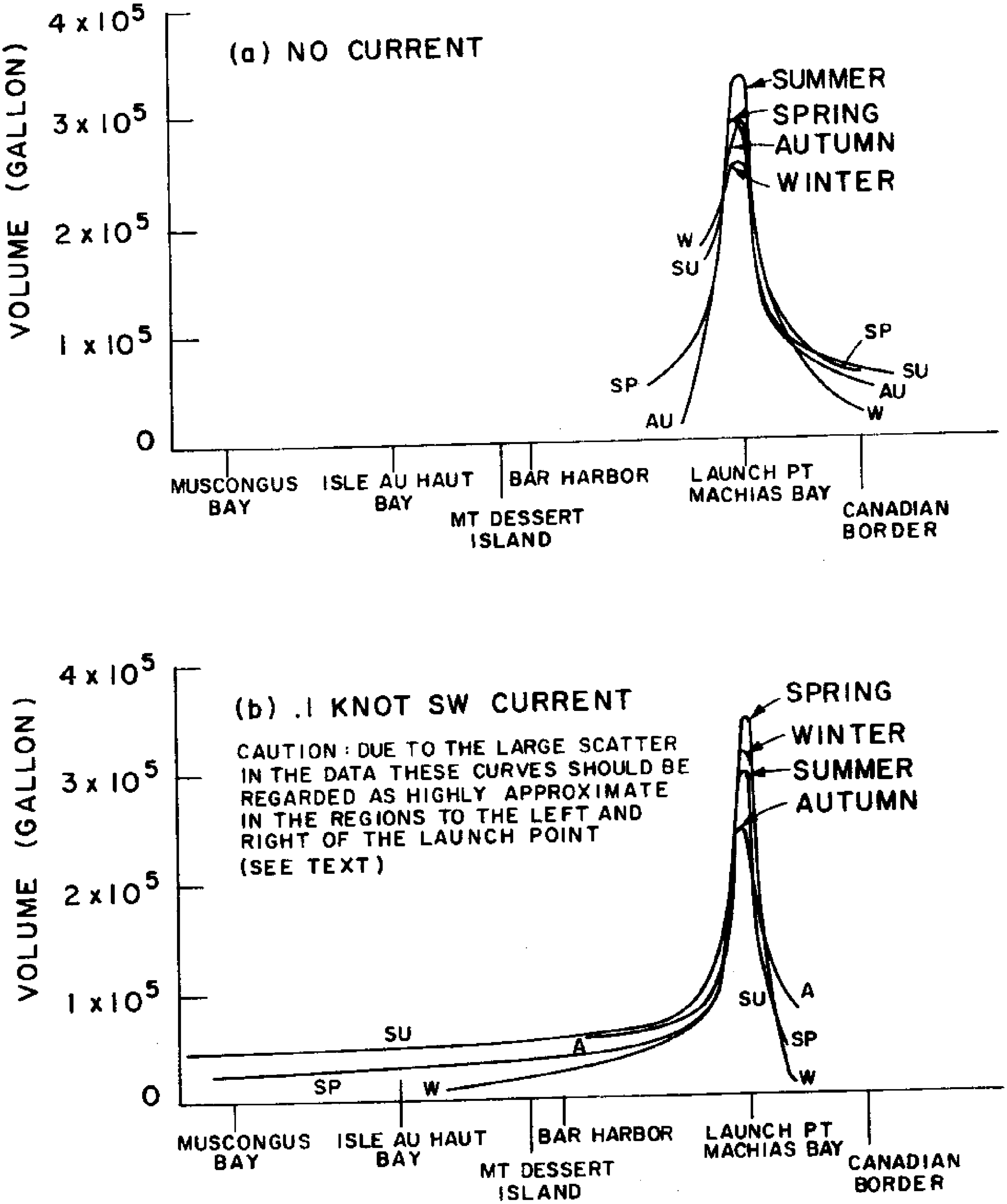


FIGURE II-2-16 AVERAGE VOLUME RETAINED BY 1.8 nm LENGTH OF SHORE GIVEN SPILL WENT ASHORE. ABSORBING, IDEALIZED SHORELINE; LAUNCH POINT 1 nm OFF IDEALIZED COAST; 1 MILLION GALLON SPILL

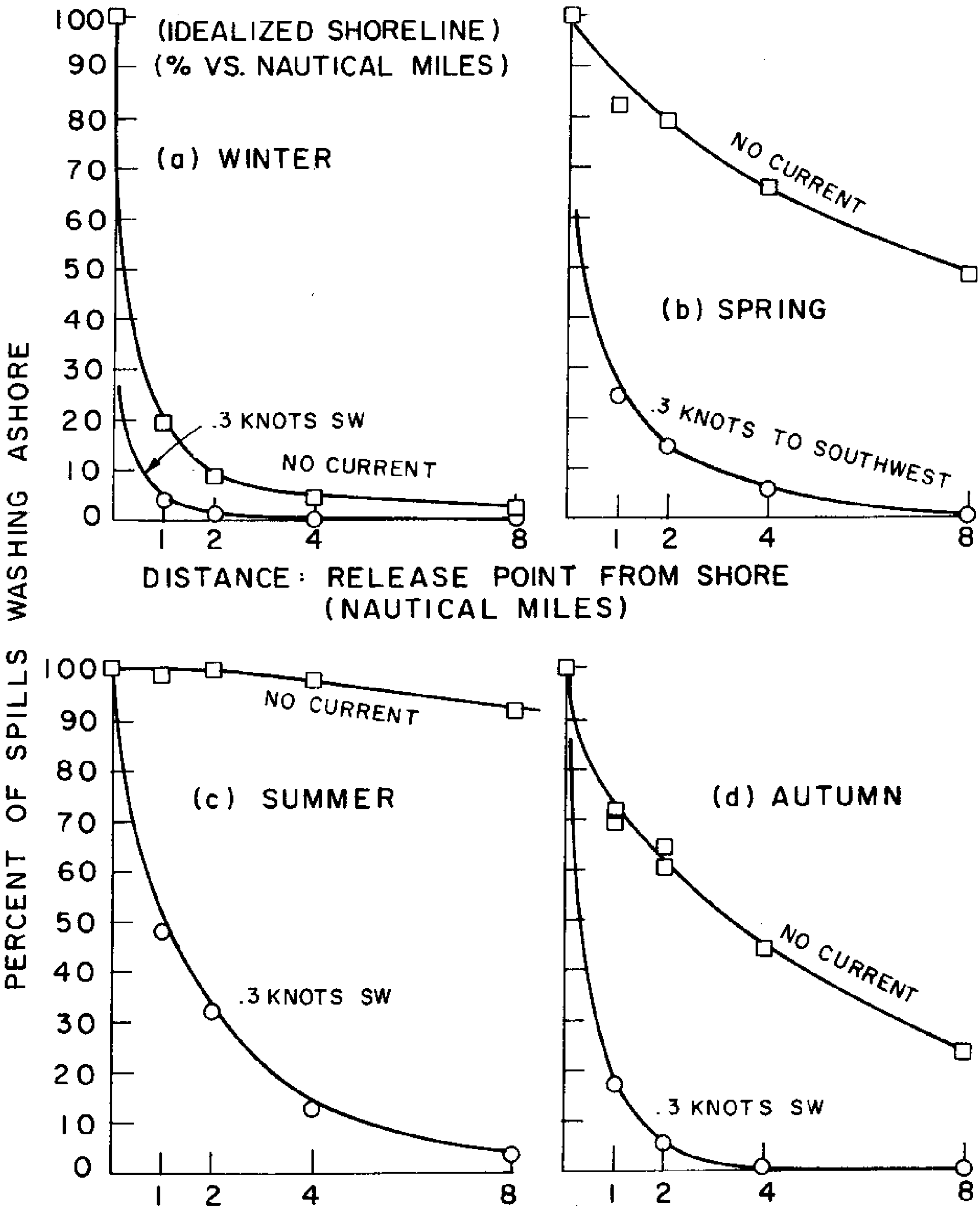


FIGURE II-2-17 SEASONAL PROBABILITY THAT A SPILL WILL BE WASHED ASHORE FOR LAUNCH POINTS VARIOUS DISTANCES OFFSHORE of mass of the spill will be blown ashore. If there is no current, then the same statement generally holds, except for summer, when just about everything spilled will be blown ashore. These results are independent of volume, as the trajectory of the center of mass of the spill was used to determine impact.

We have so far considered only the Maine shoreline as a possible point of impact. Also threatened are the northern Massachusetts shoreline and the Bay of Fundy. Figure II.2.18 presents the percentages for probable impact for these two regions as a function of season. The non-absorbing shoreline model was used to insure a conservative "over"-estimate of this property. (Note: a spill was counted as a probable impact if it passed into the Bay of Fundy or if it passed within 30 miles of Portland, Maine.)

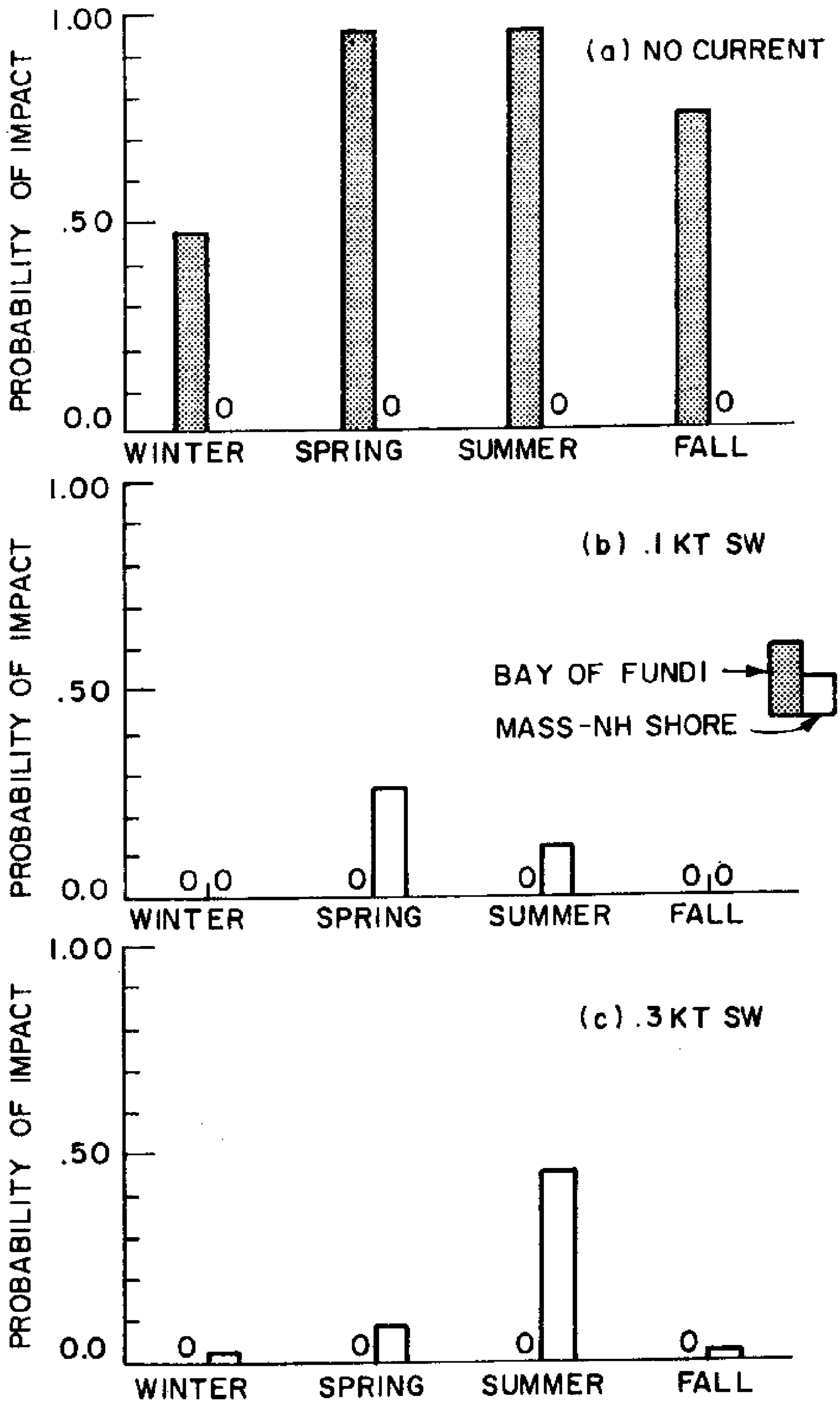


FIGURE II-2-18 PROBABILITY OF IMPACT OF 1 MILLION GALLON SPILL, PRESUMING NON ABSORBING SHORE. LAUNCH POINT 1 MILE OFF IDEALIZED SHORE AT MACHIAS BAY.

II.2.9 Volume dependence

In addition to the one million gallon spill discussed in previous sections, a ten million gallon spill was investigated for the .1 knot SW current and the absorbing shoreline presumption. The anticipated results were that (a) the probability of a length of shore being touched at least once would increase, particularly in the tail of the distribution, and that (b) the amount of oil absorbed per length of shoreline would also increase. These proved to be generally the case. Figure II.2.19 shows the probability that the shore will be touched at least once in the life of a ten million gallon spill, presuming the shore behaves like an absorbing boundary. Note that the probabilities near the peak are almost identical to those of Figure II.2.14 B, but that in the portion of the tail immediately to the left of the peak, the probabilities are nearly twice as large, being on the order of 10% during summer at approximately Mt. Desert Island, 3 or 4% for the one million gallon spill at the same point. Far to the left, the probabilities tend to lie together in the 1 to 2% range.

The average amount of oil deposited on a 1.8 mile length of shore per spill incident was determined and it was found that except for a factor of ten, the curves of Figure II.2.15.6 depicted the behavior fairly well. The significant difference lay in the amount of oil deposited in the region far to the left of the launch point. In this region, the amount of oil deposited was small in proportion to the amount launched, so the graphic representation utilized in Figure II.2.15 would fail to show the difference between zero and this amount. However, the amount was still substantial from a pollution standpoint. Table II.2.5 summarizes this effect by noting the distance south to the last point impacted by a portion of the original spill and the amount deposited for the one million and ten million gallon spills, for each season. Since we are dealing in the tail of this

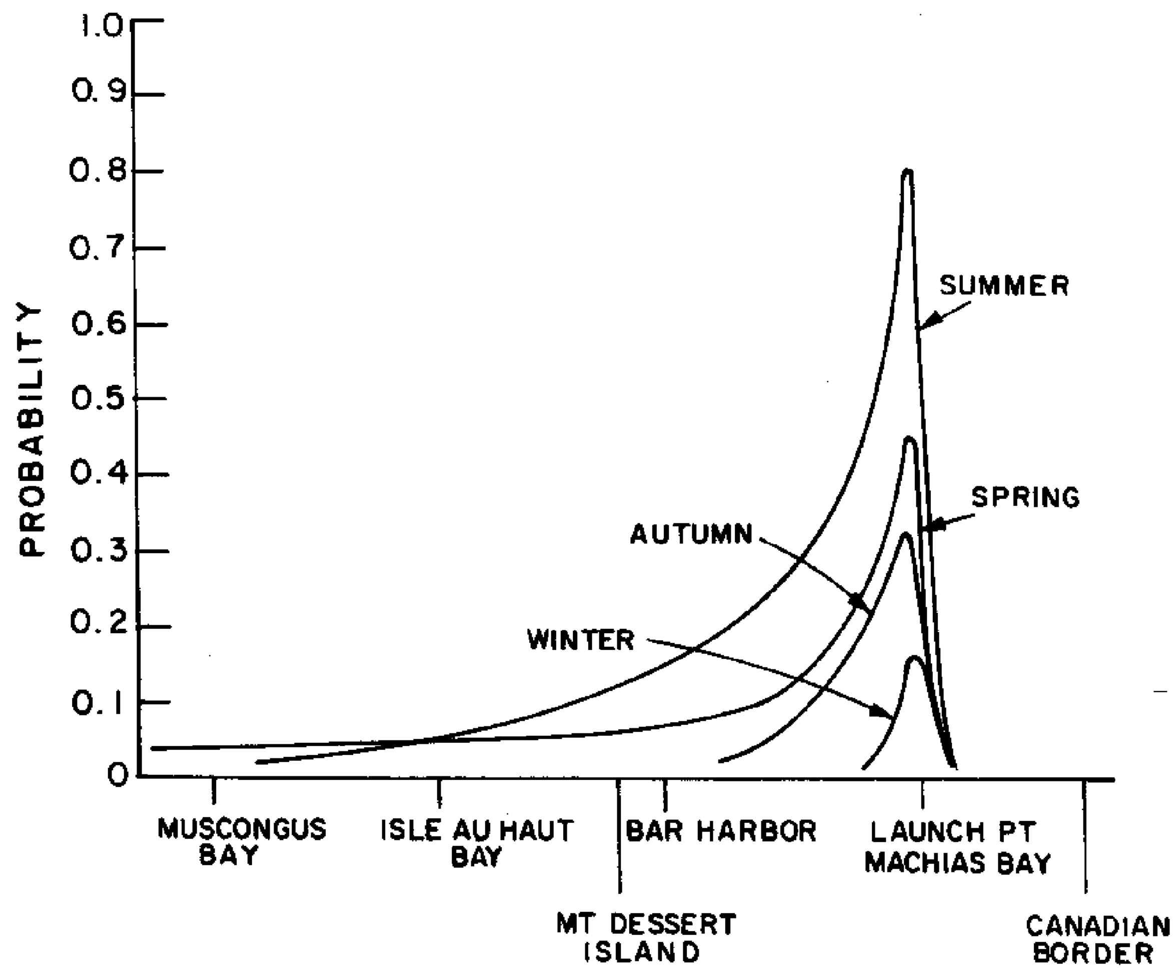


FIGURE II-2-19 PROBABILITY THAT A 1.8 nm LENGTH OF SHORE IS TOUCHED ONCE DURING LIFE OF SPILL. ABSORBING, IDEALIZED SHORELINE; 10 MILLION GALLON SPILL; LAUNCH PT. 1nm OFF IDEALIZED SHORE; .1 KNOT SW CURRENT

Season	One Million Gallon Spill		Ten Million Gallon Spill	
	Distance to Last Impact Point, Measured South from Machias Bay (NM)	Amount Deposited Given Spill Hit Shore* (gallons)	Distance to Last Impact Point, Measured South from Machias Bay (NM)	Amount Deposited Given Spill Hit Shore* (gallons)
Winter	57 (Isle Au Haut Bay)	9×10^3	57 (Isle Au Haut Bay)	1.6×10^5
Spring	130 (Portland)	2.8×10^4	130 (Portland)	2×10^5
Summer	97 (Muscongus Bay)	6.4×10^3	102 (Muscongus Bay)	5×10^4
Autumn	40 (Bar Harbor)	1×10^3	49 (Mt. Desert Island)	3.6×10^4

*Note: the probability of the spill going ashore is very small, typically .5%.

Table II.2.5

distribution, the uncertainty in these numerical values is large. However, the order of magnitude is probably accurately determined. Note that the values still tend to be different by approximately an order of magnitude, indicating that the spills don't rub down the shoreline, slowly losing material, but rather, they probably impact it once or twice prior to their final collision, bouncing well offshore in between impacts, and then drive themselves completely into the tidal region.

It must be remembered that the assumption of the absorbing shoreline is our "best" case result, giving us a lower bound on the region affected. In an actual spill incident, we might say that the behavior of a large patch of the original slick is given by this estimate. However, remnants due to secondary launchings or excursions into tidal regions that did not result in headings would increase the volume flowing south and the probability that a length of shore would be polluted.

References

Bigelow, H. B., 1927, Physical Oceanography of the Gulf of Maine, Bulletin of the U.S. Bureau of Fisheries, 40, Part 2: 511-1027.

Bumpus, D. F., 1961, Drift Bottle Records for the Gulf of Maine, Georges Bank and Bay of Fundy, 1956-1958, U.S. Fish and Wildlife Service, U.S. Department of the Interior.

________, and Lauzier, L. M., 1967, Surface Circulation on the Continental Shelf off Eastern North America Between Newfoundland and Florida, American Geophysical Society, New York.

Colton, J. B., Jr., 1964, History of Oceanography in the Offshore Waters of the Gulf of Maine, Special Scientific Report Fisheries, No. 496, U.S. Fish and Wildlife Service, U.S. Department of the Interior.

________, et al., 1968, Physical, Chemical, and Biological Observations of the Gulf of Maine, Nova Scotia to Long Island, 1964-1969, U.S. Fish and Wildlife Service, Data Report No. 23.

Day, C. G., 1958, Surface Circulation of the Gulf of Maine as Deduced from Drift Bottles, Fishery Bulletin 141, U.S. Fish and Wildlife Service, U.S. Department of the Interior.

Fay, J. A., 1971, "Physical Processes in the Spread of Oil on a Water Surface", in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, DC.

Forrester, W. D., 1971, "Distribution of Suspended Oil Particles Following the Grounding of the Tanker 'Arrow'", J. Mar. Res., 29 (2): 151-170.

Graham, J. J., 1970, Coastal Currents of the Western Gulf of Maine, ICNAF Research Bulletin, n. 7: 19-31.

Hoult, D. P., 1969, Oil on the Sea, Proceedings of a symposium on scientific and engineering aspects of oil pollution on the sea, sponsored by M.I.T. and Woods Hole Oceanographic Institute, Cambridge, MA.

________, 1972, "Oil Spreading on the Sea," Ann. Rev. Fluid Mech.: 59-64.

Meade, R. H., after 1970, The Coastal Environment of New England, U.S. Geological Survey, Woods Hole, MA, printed and distributed by the New England River Basins Commission.

Neu, H. A., 1970, The Hydrodynamics of Chedabucto Bay and Its Influence on the "Arrow" Oil Disaster, Atlantic Oceanographic Laboratory, Bedford Institute, Dartmouth, Nova Scotia, Canada.

Phillips, O. M., 1969, The Dynamics of the Upper Ocean, Cambridge

Chapter II.3
Oil Spill Containment and Removal

II.3.1 Introduction

The two previous chapters have operated under the conservative assumption that no attempt is made to contain or clean up the spills described therein. This chapter summarizes the physics of oil spill collection and removal, develops a model for determining a preliminary model for costing booms and collection devices, and simulates these systems operating against a range of hypothetical spills in order to generate some insight into the effectiveness of these systems.

The analysis is complicated both by the large number of variables which one can manipulate in designing a spill collection and retrieval system (including boom length, strength and depth, collection device type and capacity, and time to deployment) and the large number of spills and wind and current conditions one can design to. Thus, our discussion will necessarily be somewhat general in nature. For the bulk of our quantitative analysis, we will rely heavily on Hoult (1969).

II.3.2 Containment devices

The first step in the removal process is to stop the spreading of oil by some containment device. There are two main classes of containment device - physical barriers and pneumatic barriers.

Let us first review the state of understanding of these devices. For physical booms, we have a fair understanding of the oil holding capacity of a boom in a wind and in a moderate current (less than 2 knots). The forces on a boom in a steady current have been measured for both empty and full conditions. A theory has been developed that predicts both the shape that a boom assumes when deployed in a steady current, and the volume of oil that the deployed boom will hold. The amount of buoyancy and weight required to maintain the boom in an upright position in a steady current can be calculated. While much of the data is not accurate enough to make detailed design calculations, we may say that enough is known about booms operating in moderate currents to estimate whether a given type of device is likely to work in a given situation.

Stronger currents induce a phenomenon known as head wave loss. This occurs when bubbles of oil are drawn down into the water from the body of the slick at its upstream edge in a region known as the head wave. These bubbles are carried downstream by the current. As they move horizontally, they also tend to move vertically towards the surface due to their buoyancy. If the point where the oil bubbles are drawn down into the water is too close to the barrier, many of the bubbles will flow beneath the barrier, resulting in high leakage. While this phenomenon is still being investigated, we are fairly certain that 2 knots represents the highest velocity at which we can expect a boom to operate without substantial head wave loss. This phenomenon is of particular importance because as oil is lost, the leading edge of the slick and subsequently the location of the head wave moves backwards towards the boom, provided no new oil is released into the boom. This enhances the head wave leakage because the oil bubbles have less time to float up and rejoin the slick; eventually, all the oil may be lost.

Large waves induce further limitations which make analysis and prediction intractable. First, we find that making the boom follow the sea while supporting a large tensile load leads to a fairly large and heavy structure. This imposes constraints on our delivery and deployment systems. Additionally, we find that the orbital velocity of the wave substantially increases the effective current, and may induce substantial head wave loss at lower currents than anticipated. While it is possible to design a boom with very high seakeeping capabilities, it is doubtful whether such a boom would ever be practical. Maximum sea state ability of present booms is about 5 feet. It seems unlikely that higher sea state booms will be developed.

For air barriers, the situation is similar. We have an adequate theory of how an air barrier works in a wave field, when the oil slick consists of passive blocks of oil which have no tendency to spread. We know enough about how oil is held in a current to estimate the holding capacity of an air barrier in a current, or in a wind. However, the holding capacity of an air barrier in a combined wave and current field is not known. The main practical difficulty with air barriers is the extremely large amount of power they require to resist any sizable current. In view of this difficulty, we will not consider air barriers as a prospective system.

The first step in our analysis of conventional booms will be the determination of the thickness of the oil pool h(x) at a distance x away from the barrier in a waveless, steady current under the 2 knot head wave loss limitation.

Let τ be the turbulent stress acting on the oil due to the current, U be the velocity in the oil, x the distance from the leading edge of the oil slick (x increases in the direction of U), h the oil thickness, Δ the difference in the specific gravities of oil and water (typically 1/10), ρ the density of water, and g the acceleration due to gravity. Hoult (1969) demonstrated that if $y = 0$ is the mean water level, the oil, which is very nearly in hydrostatic equilibrium, rises Δh above $y = 0$, and extends to $y = -(1 - \Delta)h$ below the water surface (just like an iceberg). A balance of forces acting on the oil yields the following equation (see Figure II.3.1):

$$\frac{d}{dx} \int_{-(1-\Delta)h}^{\Delta h} \rho U^2 dy + \rho g \Delta h \frac{dh}{dx} + \tau = 0 \tag{1}$$

$$\int_{-(1-\Delta)h}^{\Delta h} \rho U dy = 0 \tag{2}$$

In equation (1), the first term is the rate of change of momentum in the oil (where we have approximated the oil density by ρ), the second is the hydrostatic force in the horizontal direction, and the third is the turbulent stress.

Now, previous results (Hoult, 1969) have shown that when the wind piles down oil against a barrier in still water, the motions in the oil are negligible, and the stress is not a strong function of x. Thus, by ignoring the first term in equation (1), and assuming τ is constant, equation (1) may be integrated. The observations reported by Hoult (1969) are in good agreement with this theory.

But, when a current is present, appreciable motions are observed in the oil. They may be described as consisting of two parts: (a) a mean motion in the direction of the current near the lower surface of the oil, and a reverse flow on the upper surface; and (b) a pattern of

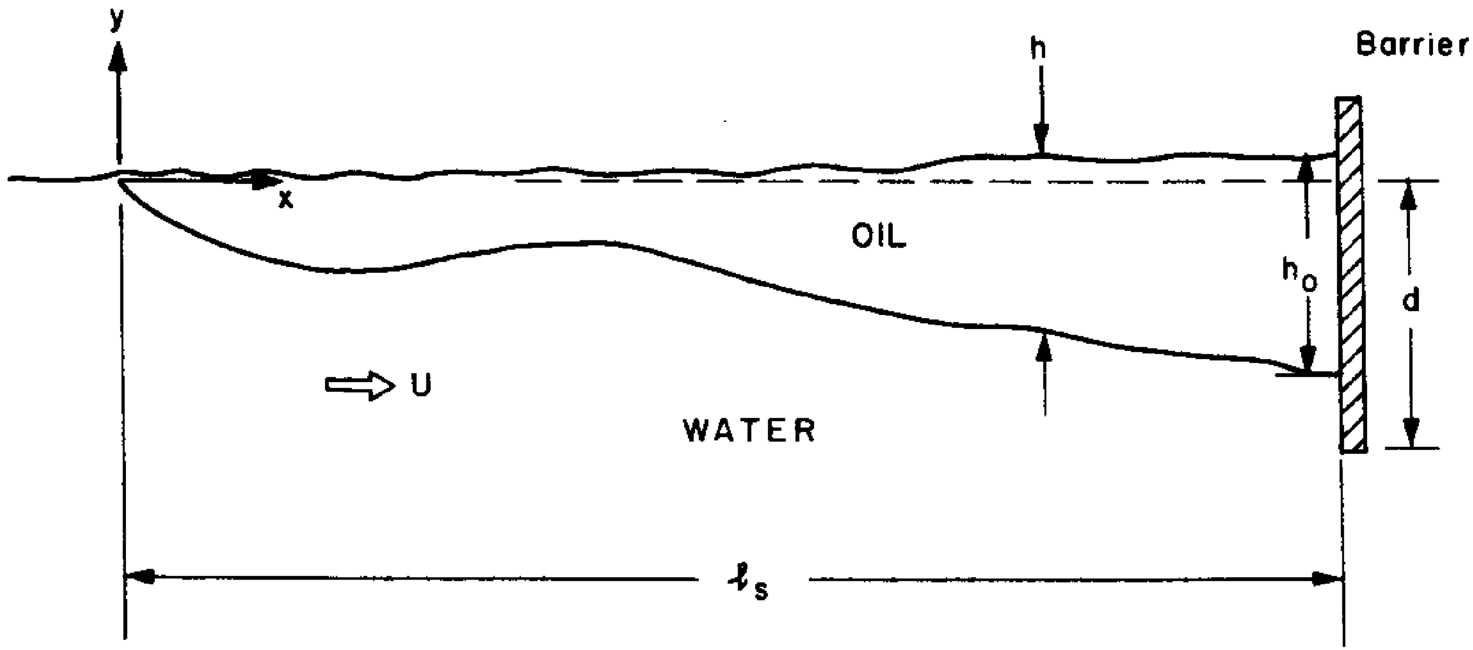


FIGURE II-3-1 SKETCH OF SIDE VIEW OF OIL CONTAINED BY VERTICAL BARRIER random waves on the oil-water interface. The upper surface of the oil is quite smooth, even though the lower surface, a short distance below, is rough with these waves. Thus, only an observer viewing the oil slick from the side or below would notice their presence. We shall see that (a) and (b) have profound consequences for the holding capacity of barriers. Similar descriptions, but no data, have been given previously by Wilkes (1969).

Because we have measured neither U in the oil, nor τ in the water, but only h, the mean oil thickness, equation (1) cannot be integrated as it stands. However, an extensive experimental study by Cross and Hoult (1970) has shown that the thickness h, as a function of x, is not a strong function of the oil viscosity. Provided appreciable amounts of oil are held by the barrier, the slick will extend far upstream of the barrier. Since the length to which the slick extends upstream of the barrier may be 100 times larger than the depth of the barrier, and since the barrier geometry can influence the motion of the oil slick at most only a few depths upstream, it is clear that when a lot of oil is held by a barrier, its thickness distribution must be independent of the shape and construction of the barrier.

If we assume that the thickness distribution is independent of viscosity, we arrive at the conclusion that h can only be a function of x, $g\Delta$ (since Δ always occurs in combination with g, as in eq. (1)), U, and ρ. A dimensional argument then yields

$$h = \frac{U^2}{g\Delta} f\left(\frac{xg\Delta}{U^2}\right) \qquad (3)$$

For oil with viscosities 10 times greater than water, a good empirical fit to the data is given by

$$\frac{hg\Delta}{U^2} = C_f^{1/2}\left(\frac{xg\Delta}{U^2}\right)^{1/2} \qquad (4)$$

where C_f is the friction coefficient.

The Reynolds number based on distance from the leading edge of the slick is high enough so that the skin friction coefficient is independent of size. The value of C_f for soya oil is 8.1×10^{-3} ($C_f = \tau/\frac{1}{2}\rho U^2$); the value for fuel oil is 30% less, but the difference is only as large as the scatter in the data.

We next consider the pressure fluctuations in the turbulent boundary layer in the water at the oil-water interface, for these will determine the depth of the boom required to prevent leakage. If the oil velocity is a small fraction of U, then these pressure fluctuations, p', may be estimated to be

$$p' \sim \rho U\, U' \tag{5}$$

where U' is the fluctuating velocity field in the turbulent boundary layer. Typically, $U' \sim \frac{2}{10} U$.

Suppose now that these pressure fluctuations are balanced by fluctuations in the depth of the oil layer. Then the size of such fluctuations in h may be estimated as

$$\rho g \Delta h' \sim p' = \frac{2}{10}\rho U^2 \tag{6}$$

If the combination of the mean depth of the oil, h, plus h', is bigger than the depth of the barrier, then the barrier leaks oil. On the other hand, to have a well-developed boundary layer at the oil-water interface, h' must be less than h. For large U, it is observed that h' is typically 1/2 h. Hence if

$$d > h' + h \doteq 3h' = 3\left(\frac{2}{10}\right)\frac{\rho U^2}{\rho g \Delta} \tag{7}$$

then the barrier leaks oil. This argument implies, by equation (7), that there is a <u>critical Froude number above which the barrier will leak oil</u>. From equation (7), we may estimate the critical Froude number to be

$$F_{critical} \cong 1.30 \tag{8}$$

This critical Froude number limitation relates to leakage measured in the region of the barrier. It is to be distinguished from head wave loss, which occurs at the upstream edge of the slick.

The foregoing allows us to determine the depth of a boom required to resist leakage in calm water for a given current and oil-pool length. The next problem is to determine the shape which the boom will assume and the strength required to resist the piled-up oil.

Consider now a barrier composed of a vertical flat plate oriented so that it is normal to the current. This configuration is typical of many commercially available booms.

If we suppose that the Reynolds numbers of the flow are so high that the main features of the flow around a vertical flat plate are independent of viscosity, then the drag, D, is a function of the current, the buoyancy forces, the volume of oil held, the oil density, and the water density. To simplify the discussion, it is convenient to consider two limiting cases: (1) when no oil is held and (2) when the barrier holds the maximum possible oil, and the slick extends a long distance upstream.

In the first case, a dimensional argument shows that

$$D = \frac{1}{2}\rho U^2 d C_D \quad , \quad C_D = C_D(U/\sqrt{gd}) \tag{9}$$

Robbins (1970) demonstrated that C_D is a weak function of $U/\sqrt{gd}$, the Froude number. Typical values lie between 1 and approximately 1.75, depending on the Froude number.

In the second case, when the barrier is full of oil, if we assume a hydrostatic pressure distribution on both sides of the barrier, then

$$\frac{1}{2}\rho U^2 d C_D = \frac{1}{2}\rho g \Delta d^2 \tag{10}$$

This yields

$$C_D = 1/F^2 \tag{11}$$

where F is the densimetric Froude number. Now, it is probably true that on the oil side of the barrier, the pressure is very nearly hydrostatic, because the velocities in the oil are quite low compared to the water velocity. However, on the back side of the barrier, we would expect some pressure recovery, due to the eddy formed in the barrier wake. Thus, equation (11) is only an estimate of the drag of a flat plate barrier filled with oil.

To compute the shape that an oil boom takes in a current, it is necessary to know how the drag force acting on a unit length of barrier depends on the angle, θ, the boom makes with the current. See Figure II.3.2 for a sketch of the coordinates used here. Now, x is the distance from the apex of the barrier, parallel to the current, and y is perpendicular to the current. Since the momentum in the current normal to the barrier is $\rho U^2 \cos^2\theta$, it is natural to assume that the drag coefficient has a $\cos^2\theta$ dependence:

$$C_D = C_D(\theta = 0)\cos^2\theta \tag{12}$$

$C_D\cos^2\theta$ is then the force coefficient in the direction normal to the boom.

For simplicity, we assume that the boom has zero bending stiffness. The force acting tangent to the boom is generated by viscous effects as the fluid slides along the barrier. As the Reynolds numbers are high, we may expect that these forces are small compared to the normal force. For simplicity, we set these tangential forces equal to zero.

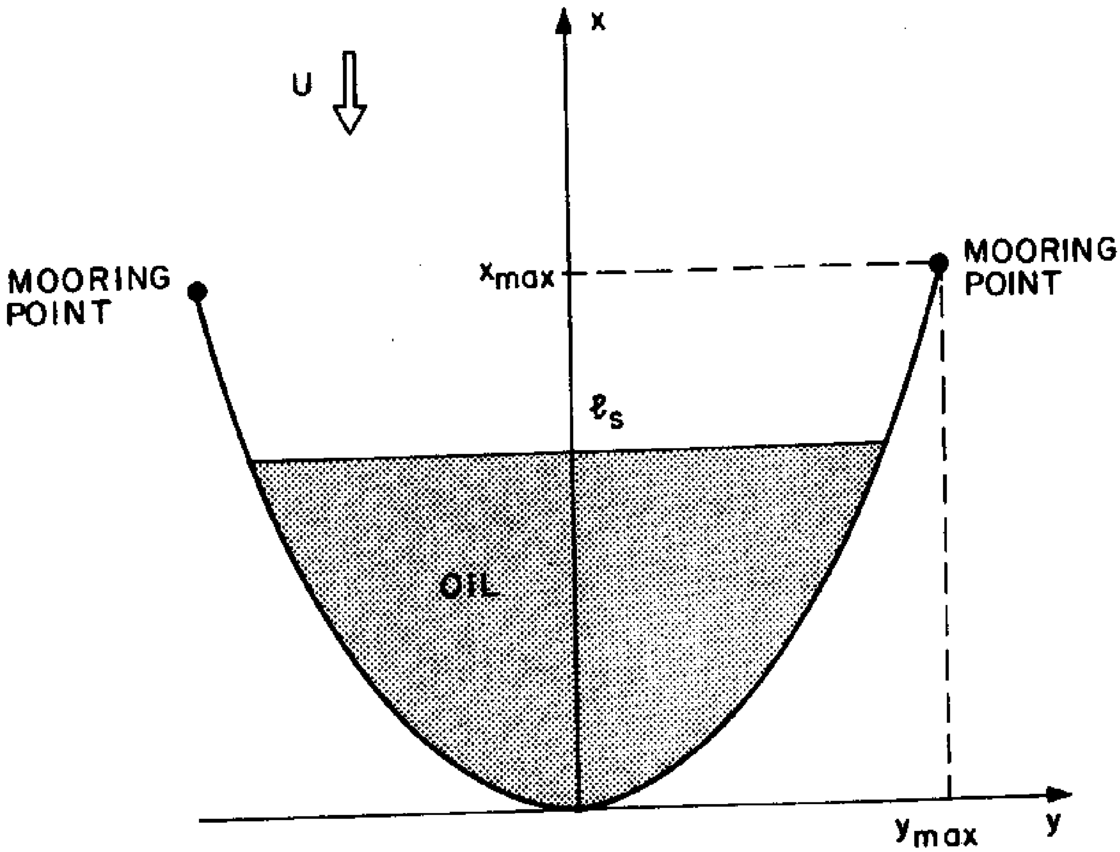


FIGURE II-3-2 SKETCH OF PLAN FORM OF OIL BOOM IN A CURRENT

Under these assumptions, it may be shown that the tension T in the boom is constant and that the normal force is balanced by the tension divided by the local radius of curvature of the barrier. Integrating the resulting differential equation under the constraint that the boom lies normal to the current at its apex leads to

$$\frac{x}{L} = \lambda\left(\cosh\left(\frac{y}{L\lambda}\right) - 1\right) \tag{13}$$

where y is the width of the boom at a distance x from the apex. L is the boom length and

$$\lambda = T/(.5\rho \cdot U^2 \cdot d \cdot C_D(\theta=0) \cdot L) \tag{14}$$

From this equation, the maximum width of a boom of length L is

$$y_{max} = L\lambda \sinh^{-1}(1/2\lambda) \tag{15}$$

The volume of the oil held by the boom is given by

$$V_B = \int_0^{\ell_s} y(x)h(x)dx \tag{16}$$

where h(x) is the depth of the pool as a function of x, and ℓ_s is the distance that the oil spill extends upstream from the center of the boom. ℓ_s must be less than x_{max}, otherwise oil would spill around the ends of the boom. When the boom is full of oil ($\ell_s = x_{max}$) then $C_D = \frac{1}{F^2}$ and

$$\lambda = \frac{T}{\frac{1}{2}\rho\Delta g D^2 L} \tag{17}$$

$$(F \leq 1.3)$$

Equation 16 can be combined with equations 4, 13 and 17 and solved numerically to find the maximum volume a given boom will hold in a given calm water current.

Thus, we have determined that an oil boom of a given depth in calm water will operate properly up to a critical current velocity. Above this velocity, turbulent pressure fluctuation will draw the oil down beneath the boom, resulting in high leakage. We have found equations which determine the configuration of the boom and the capacity of the boom. We have seen that the critical scaling parameter, λ, is proportional to the inverse of the depth squared provided the boom is full of oil.

These considerations represent the constraints imposed on us even in moderate currents. Additionally, head wave losses probably limit the maximum current to about 2 knots.

II.3.3 Collection devices

In most collection devices, a pair of sweeps or booms in a V shape are towed or pushed through the water; alternately, they can be anchored in a current. In either case, the effect is to force the oil into the throat or apex of the V where it can be removed by pumping or other means. The effect of the relative motion between the collector and the water (and the oil slick) is twofold: first, the undisturbed oil slick is brought to the skimmer, and second, a captive pool of oil is formed in the V of the skimmer. This pool of "trapped" oil is generally much deeper than the undisturbed oil slick, and concentrating the oil in this way greatly simplifies the actual removal of entrained water.

For a given piece of equipment, however, there are three factors which limit the rate at which oil can be swept up. The basic limitation is encountered when the oil flowing in the narrow throat, or apex of the V, reaches critical flow velocity. Attempts to increase the collection rate by increasing the pumping rate will simply increase the fraction of water pumped with the oil. Operating the skimmer at a higher speed will increase the collection rate until either the thickness of the captive pool reaches the depth of the skimmer booms inducing draw down or head wave leakage, or until the captive pool extends forward beyond the skimmer booms, at which point the front of the pool spills around the ends of the booms.

The important parameters in the physics of the throat region and the captive pool can be described by a simple dimensional argument. In this type of flow, there are three terms in the one-dimensional equation of motion for the oil which must be taken into account:

1) Inertia, which is of the order of $\rho h U_o^2 w$

2) Pressure (gravity), which is of the order of $\rho g \Delta h^2 w$

3) Friction from the water flowing under the oil, which is of the order of $\frac{1}{2}\rho(U_w - U_o)^2 C_f wx$

where ρ = mass density of either water or oil; h = local oil thickness; U_o = flow velocity of the oil; U_w = flow velocity of the water; w = local width between barriers; g = acceleration of gravity; C_f = turbulent shear stress coefficient; and Δ = fractional density difference between oil and water. Typical values for C_f lie between .005 and .008. The horizontal coordinate, x, is related to w and the barrier angle to the flow, θ, by $w = 2\theta x$.

The ratio of inertia to gravity forces at any section is given by the densimetric Froude number, F':

$$\frac{\rho h U_o^2 w}{\rho g \Delta h^2 w} = \frac{U_o^2}{g\Delta h} = (F')^2$$

Near the throat, U_o is large, and the Froude number approaches 1 as inertia and gravity forces predominate. Well upstream, in the captive pool, U_o is negligibly small, and inertia forces are unimportant.

The ratio of inertia to viscous (friction) forces can be written as a Reynolds number:

$$\frac{\rho h U_o^2 w}{\rho(U_w - U_o)^2 C_f wx} = \frac{2U_o^2 h\theta}{(U_w - U_o)^2 C_f w} = R$$

Near the throat, $U_w \approx U_{oil}$ and $w \approx h$. Since θ needs to be ≈ 0.2 to assure uniform conditions across the channel, R becomes very large, and friction becomes unimportant. In the captive pool, however, $U_w \gg U_o$ and $w \gg h$, so R becomes very small and inertia again becomes unimportant.

The limiting flow will occur when conditions of critical flow are reached in the throat of the collector.

We can apply energy conservation to relate this flow to the maximum depth just upstream in the captive pool. If U_t and h^t are the oil velocity and thickness in the throat and h_o is the maximum oil thickness in the captive pool, then

$$h_o - h_t = \frac{{U_t}^2}{2g\Delta} \qquad (18)$$

Since at critical flow the velocity head is always half the critical depth, $h_t = 2/3\ h_o$, and U_t can be written $U_t = (2/3\ g\Delta h_o)^{1/2}$. From this, an expression for the discharge through the throat, based on the throat width w_t and upstream depth h_o, follows:

$$Q_t = \frac{2}{3}\, h_o w_t \left(\frac{2}{3}\, g\Delta h_o\right)^{1/2} \left(= u_t w_t h_t\right) \qquad (19)$$

A comparison between oil flow rates calculated from the measured maximum depth in the pool and the throat width and the flow rate as determined by direct measurements is quite good.

Equation (4) and the critical flow analysis can be combined to predict the performance of a skimmer device. Rewriting equation (4) in terms of the maximum depth of the pool, we have:

$$h = {C_f}^{1/2} \left(\frac{U^2}{g\Delta}\right)^{1/2} {\ell_s}^{1/2} \qquad (20)$$

Utilizing this depth as an estimate of the maximum depth upstream of the throat, we can determine the maximum flow rate as a function of the length of the slick. Combining (19) with (18) yields:

$$Q = \frac{2\sqrt{2}}{3\sqrt{3}} \left(C_f\right)^{3/8} (g\Delta)^{1/2} {\ell_s}^{3/4} \left(\frac{U^2}{g\Delta}\right)^{3/4} w_t \qquad (21)$$

Both containment and collection rely on the collecting boom to gather in a significant volume of oil. If the oil has been allowed to spread to its limiting area, then the booms must be very large to encompass the oil. As a general rule, containment devices should be deployed in an amount of time on the order of that associated with the inertial spreading of the oil (see Figure II.2.1). Delays causing deployment after this time result in very thin films and the requirement for containment booms much larger than those needed for just containing the volume initially spilled. Collection is also much complicated by thin films. Multiple sweeps through the area would be required if sufficiently large booms are not available (which seems certain) and the skimmer would ingest large amounts of water due to the low pool depths and subsequent choked oil flow.

These considerations are particularly important for spills of a small to moderate size. Very large spills, such as the "Torrey Canyon" have tended to occur over the course of several days, thus the process is continuous in nature and not instantaneous. The rate of spillage and the desired containment effectiveness determine the deployment time for these spills. Smaller spills will probably occur in minutes or hours, and it is for these spills that the rate of spreading determines the required deployment time and boom size.

II.3.4 Feasibility of containment and clean-up operations in the New England region

The state of the art of containment devices limits their use to those regions in which the current is certainly less than 3 knots and the significant wave height is less than five feet. This implies that containment in harbors and other protected waters is feasible, provided the equipment can be deployed. In one or two unique areas high tidal currents are found (Woods Hole, for example) and containment within these regions is not feasible. However, the high currents are usually caused by a constriction of the flow and areas of lesser flow can be found within a mile or two of these regions of high tidal velocity.

With the exception of possible sea state limitations, containment operations should be feasible in all New England harbors, Nantucket Sound, Penobscot Bay, Narragansett Bay, and Buzzards Bay. Vineyard Sound has peak tidal velocities that slightly exceed 2 knots. Containment here may be considered to be marginally feasible.

Skimming operations may be carried out in higher currents, as the skimmer can be moved with the current as necessitated by the incidence of draw down or head wave leakage. The problems encountered here are those of maneuvering the skimmer and its attendant barge. It is unlikely that a skimmer could be safely and efficiently operated in a place like Woods Hole. However, over most of the rest of the sheltered waters in New England, skimming could be accomplished most of the time.

The picture offshore of New England is considerably different. Here sea-state limitations play the principle part. Table II.3.1 lists the percent of the time that the seas can be expected to be greater than 5 feet. These figures were extrapolated from a chart covering the entire North Atlantic, so they must be considered to be only a very rough estimate of the true percentages. Errors may

Table II.3.1
Monthly State of Sea for Offshore New England Waters*
(% time seas ≥ 5 feet)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Gulf of Maine	30	30	20	15	7	7	7	7	15	20	30	30
Georges Bank	40	40	25	20	10	10	10	10	20	30	35	40
Region lying off southern coast	30	30	30	20	10	7	7	7	15	20	30	30

*Extrapolated from Oceanographic Atlas of the North Atlantic, Section IV, H.O. pub. 700.

be as great as plus or minus 5 percentage points for the larger values.

Nevertheless, we can see that during the period May through August it might be possible to attempt cleanup operations even on Georges Bank, provided the equipment could survive the very rough conditions occasionally encountered (seas greater than 12 feet occur 1 or 2% of the time during the summer months). The logistics for such an operation would be very difficult, however, so such an operation would have very little chance of success unless extensive preparations had been made for this contingency.

Spills occurring closer to shore in the summer months will enjoy somewhat calmer seas, and the proximity to support bases will make logistics simpler. If it is possible to deploy the containment and collection equipment while the spill is still fairly thick, such operations should enjoy some fractional success.

The winter months present a much different picture. One to two weeks out of every month are going to have seas so high that containment and collection equipment will not work. Additionally, seas greater than 12 feet will occur 5 to 10% of the time. In these circumstances, it is doubtful that deploying the equipment would be desirable. Not only would the equipment be liable to be subjected to very vigorous conditions, but the working conditions would be hazardous to personnel, particularly in providing barge service to the skimmer, due to high seas and cold temperatures.

These conclusions are mitigated to some extent by the conclusions of Chapters II.1 and II.2. Chapter II.1 pointed out that spillage from ships in the offshore region is highly unlikely, and Chapter II.2 demonstrated that spills occurring on Georges Bank are unlikely to come ashore, particularly in the fall and winter. Attempts to provide an oil containment and collection system against winter spills on Georges Bank are presently futile, and almost certainly will remain so. A system designed to the peak of present technology might have some success against summer spills. However, the logistics of such an operation would be critical. It might be necessary to create specialized equipment that was dedicated solely to this mission. This would be extremely expensive.

II.3.5 Containment device characteristics

While a number of parameters must be considered when designing a boom, many of them specific to the intended application, it is illustrative to look at the characteristics of a boom designed to maximize its holding capacity for a given cost, assuming calm water and moderate current. Such a boom isn't too different from that typically used in practice, and it helps to fix in our minds the type of system we are interested in, and the costs we might anticipate, especially since it's clear that our focus with respect to containment and collection should be on near-shore spills.

Section II.3.2 presented the pertinent equations concerning boom capacity and performance. We will presume that the cost of a boom is given by

$$\text{Cost} = K_T \cdot T \cdot L + K_A \cdot L \cdot D \tag{22}$$

where K_T is the cost of the tensile member of the boom (typically a value on the order of 1¢/lb ft or less, and K_A is the cost of fabric and flotation devices, expressed in dollars/sq ft of boom area below the waterline.

This equation was combined with Equation (16) to determine boom costs for a variety of boom tensions, and sealing factors for a 1 knot calm water current and a Δ of .1. The resulting costs and holding capacities are shown in Figure II.3.3 assuming K_T = .01 \$/lb ft and K_A = 10 \$/ft^2. The envelope to the lower right of this graph yields maximum holding capacity as a function of boom investment. Figures II.3.4 through II.3.7 display the tension, boom length, and draft corresponding to these maximum capacity booms. An interesting feature of these optimum booms is that they are low-tension devices with very deep pockets for oil capture.

We investigated the sensitivity of this analysis to the value of K_A. For low-capacity booms, the costs

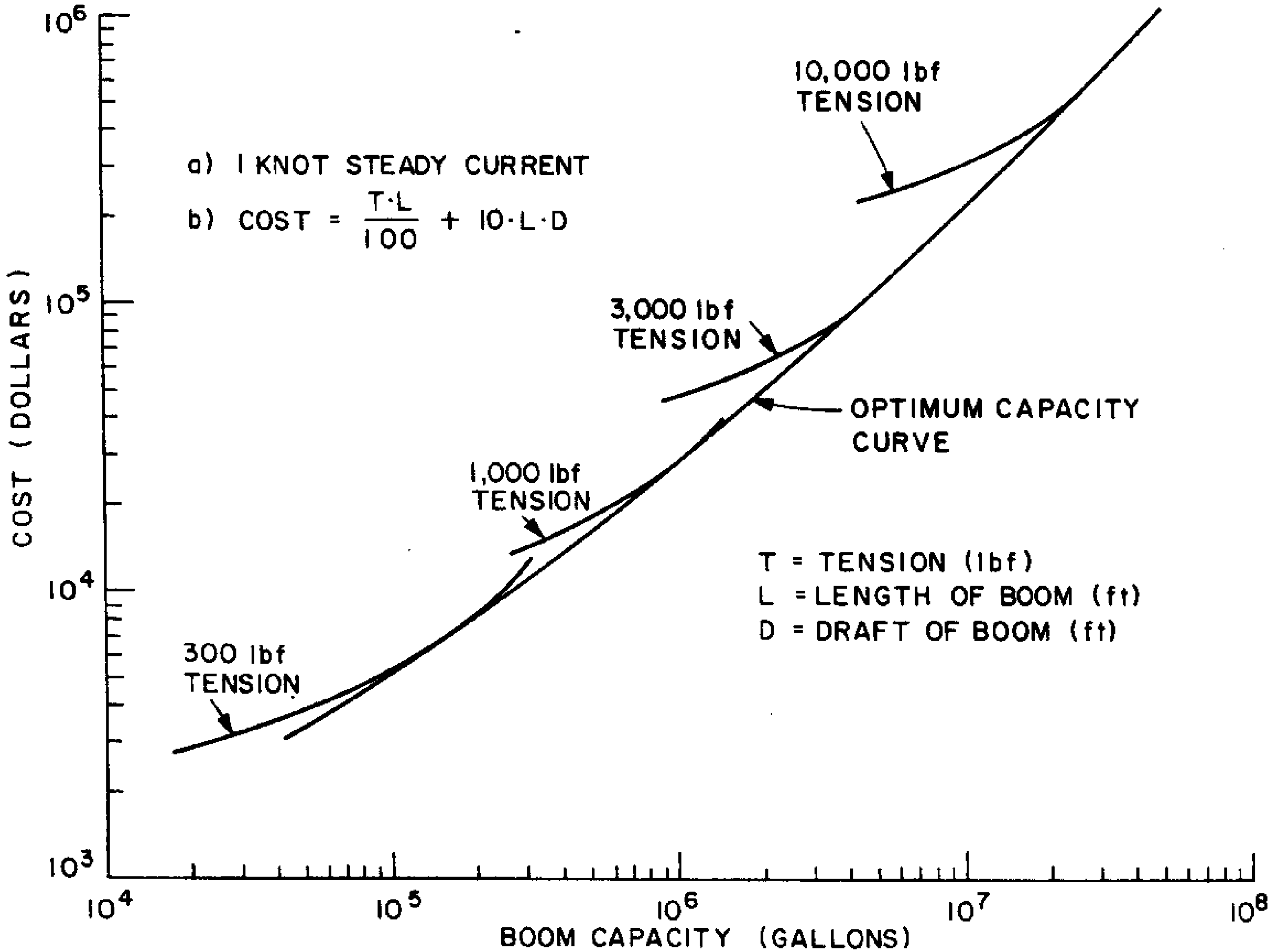


FIGURE II-3-3 COST VERSUS BOOM CAPACITY

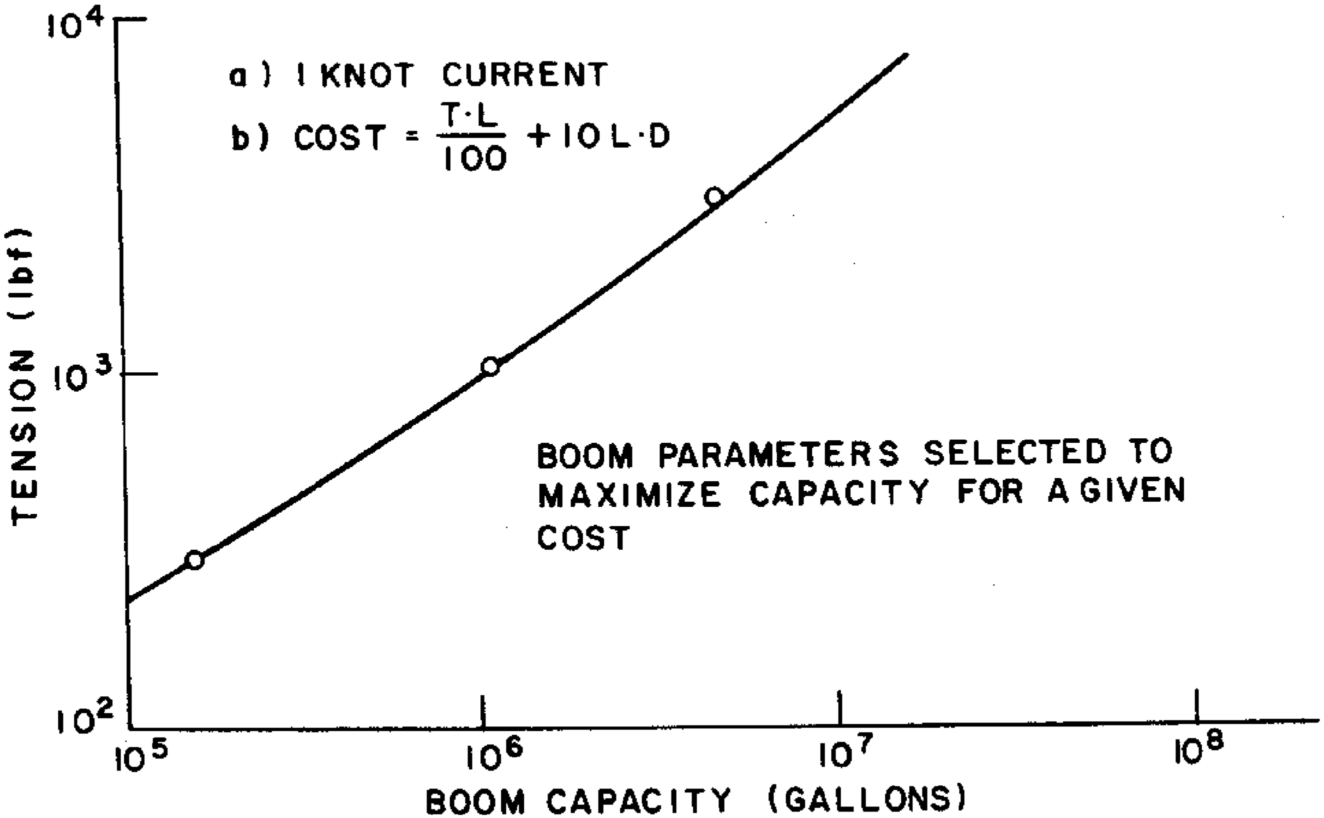


FIGURE II-3-4 TENSION VERSUS BOOM CAPACITY

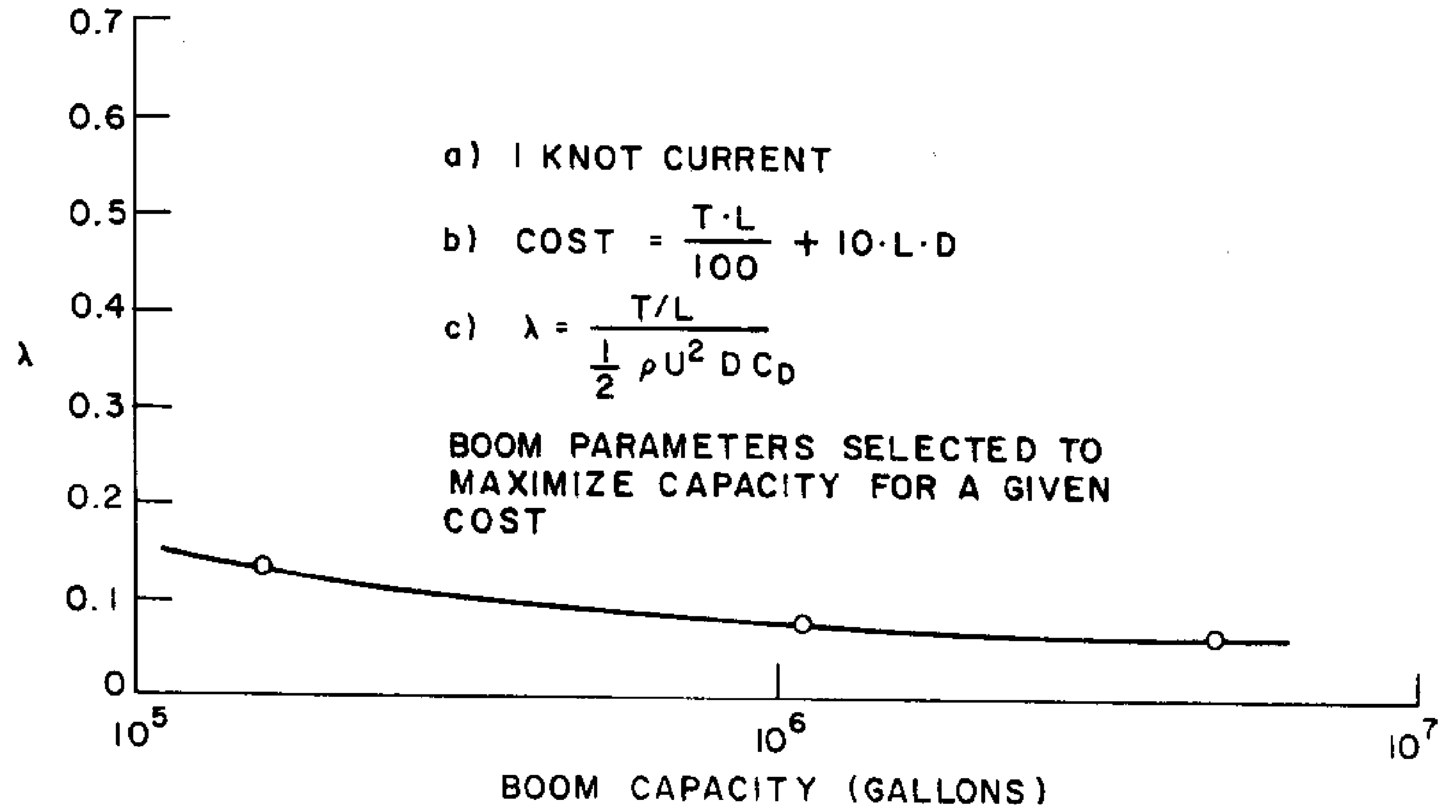


FIGURE II-3-5 λ VERSUS BOOM CAPACITY

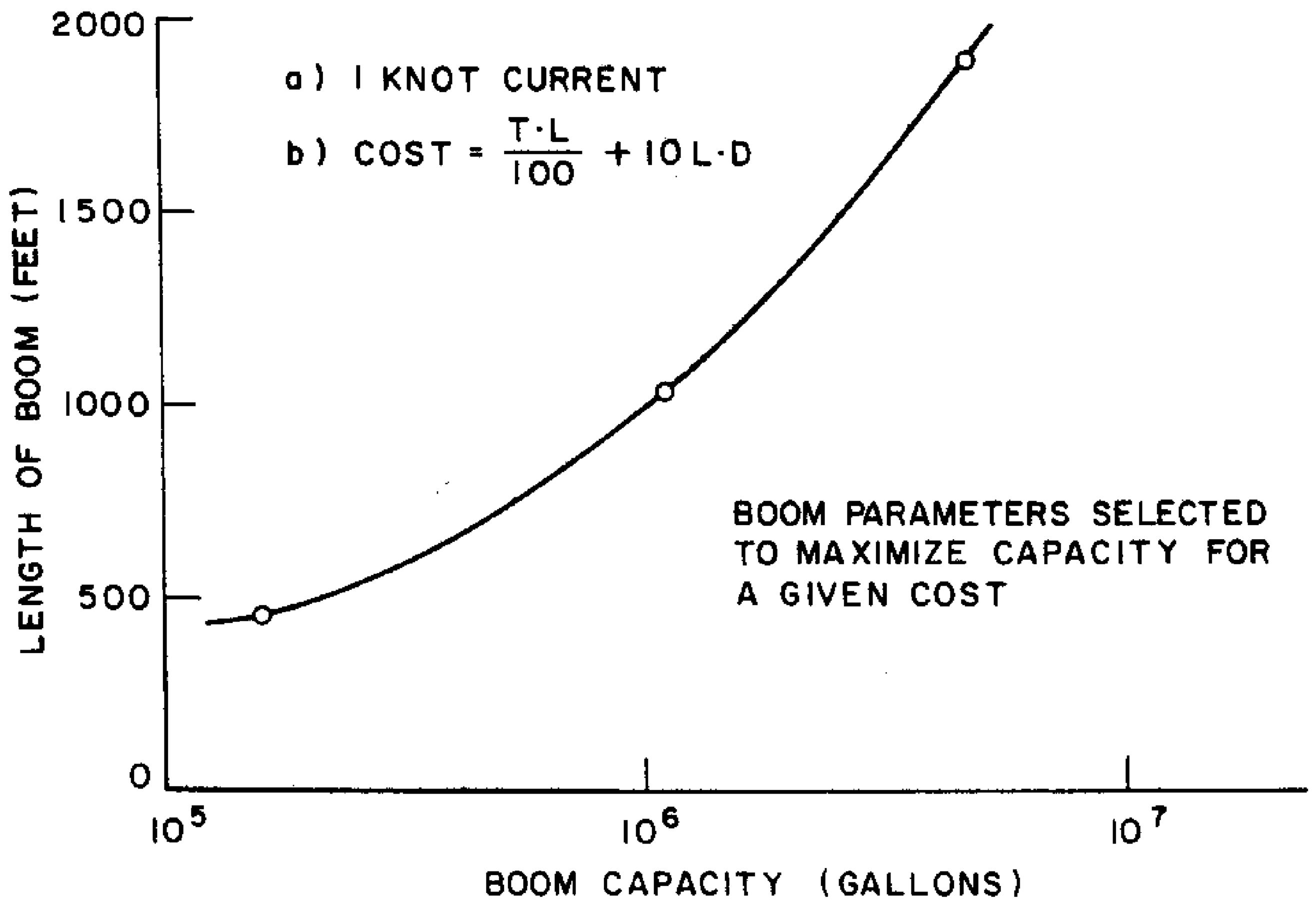


FIGURE II-3-6 LENGTH OF BOOM VERSUS CAPACITY

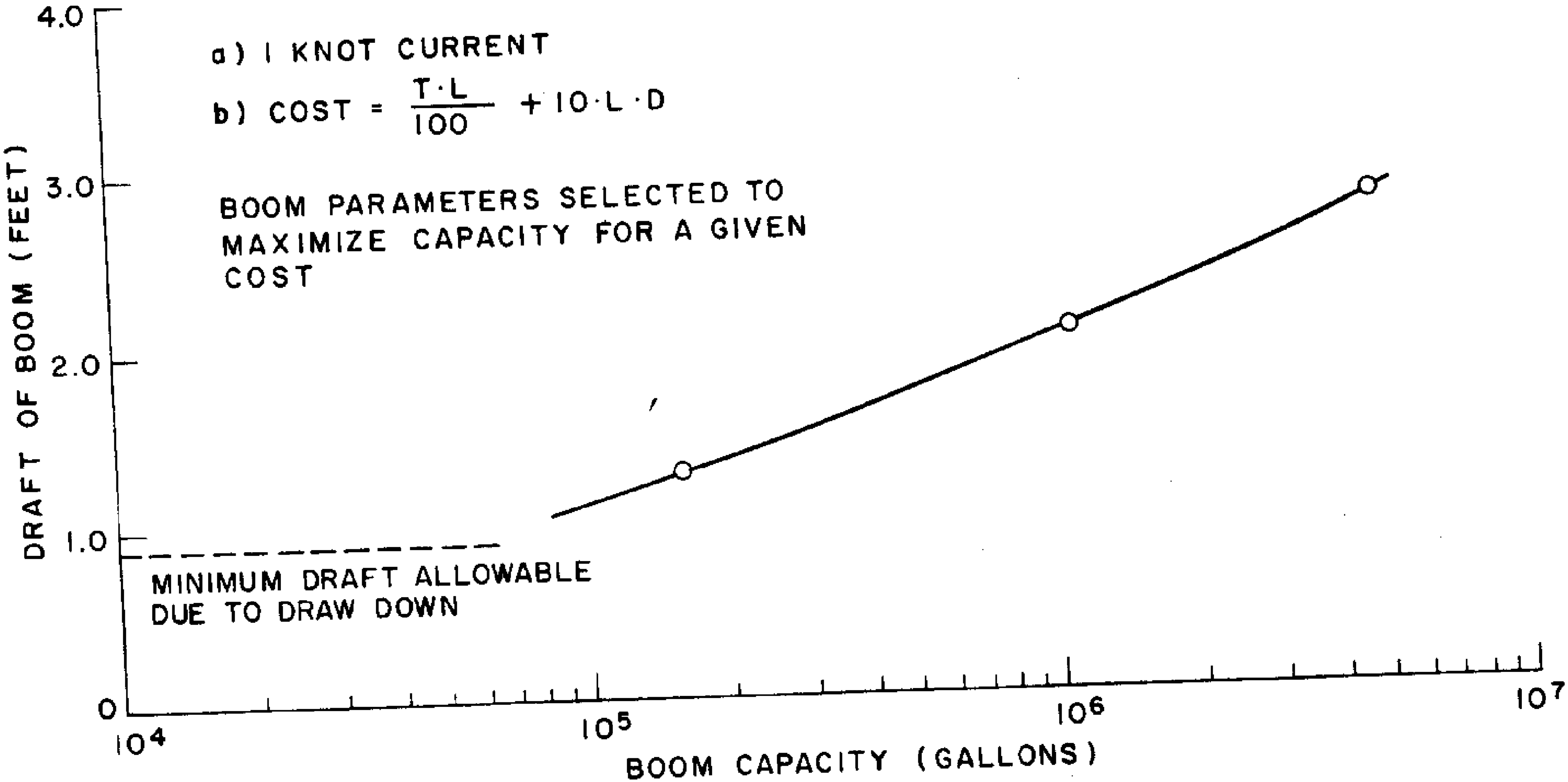


FIGURE II-3-7 DRAFT OF BOOM VERSUS BOOM CAPACITY decreased nearly in proportion to the fabric cost, K_A, and the optimum boom tended to be deeply pocketed. However, as we got into larger booms, the tensile factor became more significant, and for booms over ten million gallons capacity the variation in cost due to K_A will be overwhelmed by variation in K_T. Booms in this range still tend to be deeply pocketed. Most of these results can be anticipated from the form of the cost equation.

Having developed a means of specifying maximum capacity for a given investment, we now seek to couple the boom with the skimmer through equation (19) and the appropriate function relating the depth of the oil in the boom and the volume of oil in the boom. Presuming that the geometry of the boom does not change as the amount of oil in the boom varies, it can be shown that in a specified current the volume of oil held within a given boom varies approximately as the fourth power of the depth. This implies that the flow rate Q varies as the volume to the three-eighths power, i.e.

$$Q \sim V_B^{3/8}$$

In order to determine the constant of proportionality, we took five representative booms selected from our family of optimum booms and numerically calculated the depth of oil in the boom versus the volume held. Figure II.3.8 shows the results of this calculation for a 1 knot current. Remarkably enough, the curves for all five booms fell almost exactly on a line given by

$$h_o = 4.67 \times 10^{-2} V_B^{1/4} \qquad (23)$$

This occurred because the product of L and λ does not vary by more than a factor of two over the range of optimum booms investigated. It may be shown that the volume of oil held by the central portion of a boom is proportional to this factor to the 1/2 power. Thus, when we take the volume of the boom to the quarter power, the λL factor is

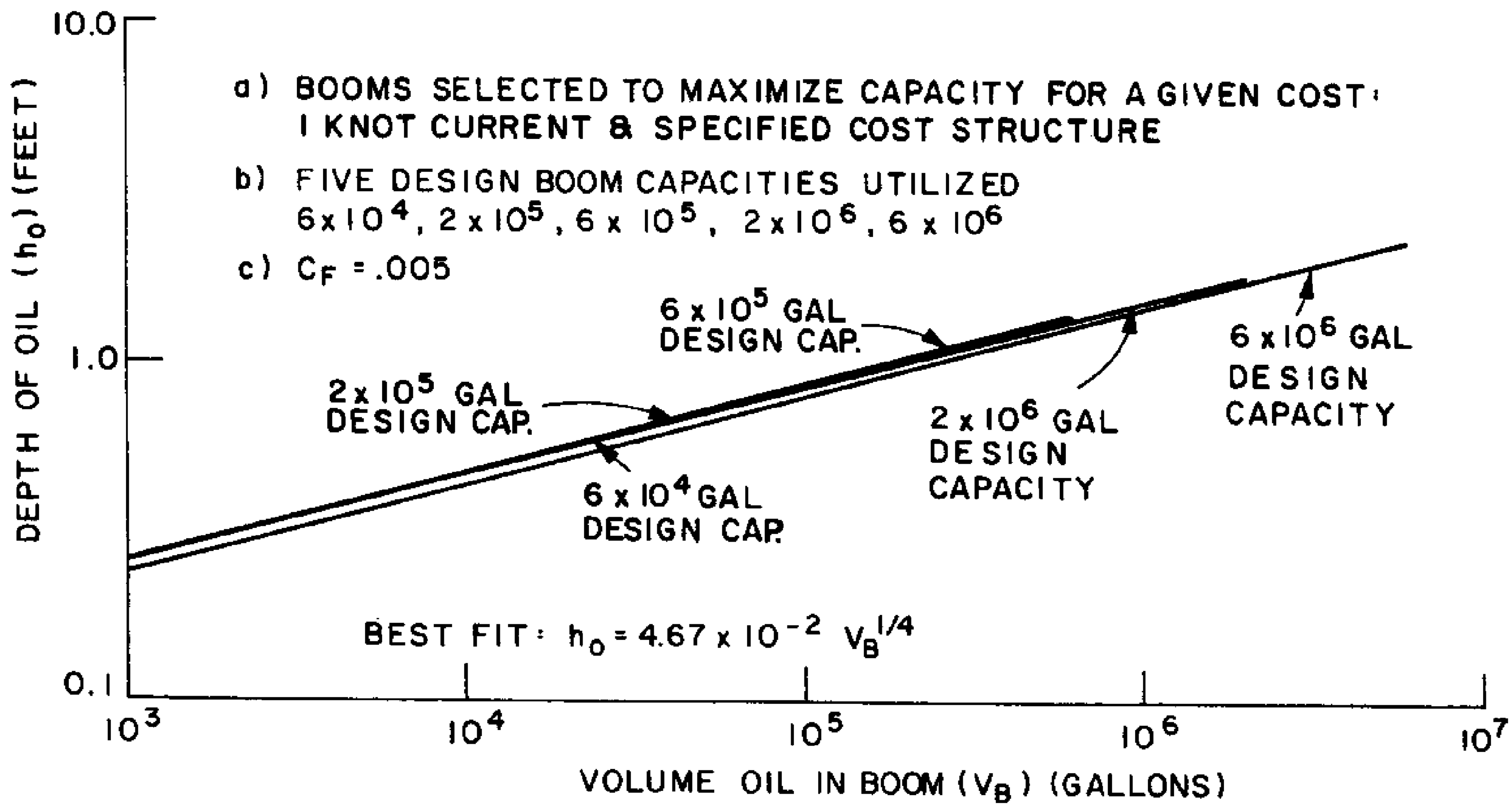


FIGURE II-3-8 DEPTH OF OIL VERSUS VOLUME OIL IN BOOM raised to the 1/8 power and the initial difference disappears.

Combining (23) with (19) we have the maximum flow that can be obtained by a skimmer working in conjunction with one of the optimum booms. It is:

$$Q_t = \frac{2}{3} w_t \left(\frac{2}{3} g\Delta\right)^{1/2} \left(4.67 \times 10^{-2} V_B^{1/4}\right)^{3/2} \qquad (24)$$

II.3.6 Simulated spill incident

It seems likely that in the near future, a variety of containment and skimming devices will be readily available for deployment to the site of a spill. Typical pump capacities of skimmers now in use or under development fall in the range of 10,000 gph to 100,000 gph. Maximum capacities of containment devices tend to fall in the 100,000 gallon to 1,000,000 gallon range for currents around 1 knot.

We will investigate an extremely large, 10 million gallon spill that occurs in a harbor having peak tidal velocities of 1 knot. Further, we will presume that this spillage occurs at a uniform rate. Two spillage rates will be used, 100,000 gph and 500,000 gph. The clean-up operations will start immediately with the occurrence of the spill and we will presume that the containment device is deployed in one hour. Four boom capacities will be investigated, ranging from 60,000 gallons to 2,000,000 gallons. Skimming will not commence until barges arrive to receive the retrieved petroleum. Three barge arrival patterns will be investigated; they are depicted in Figure II.3.9. These arrival patterns represent our best guess at the worst case capabilities of the three harbor types for the New England region, provided the On Scene Commander at the spill is given the authority to divert barge traffic as required to assist in the cleanup. The twelve-hour delay until the arrival of the first barge in the major and secondary terminals presumes that no barge is in the process of offloading at the time of the spill, but rather a full barge must be emptied prior to deployment to the spill site.

The rate of change of the volume of oil contained in the boom, V_B, is given by the following differential equation:

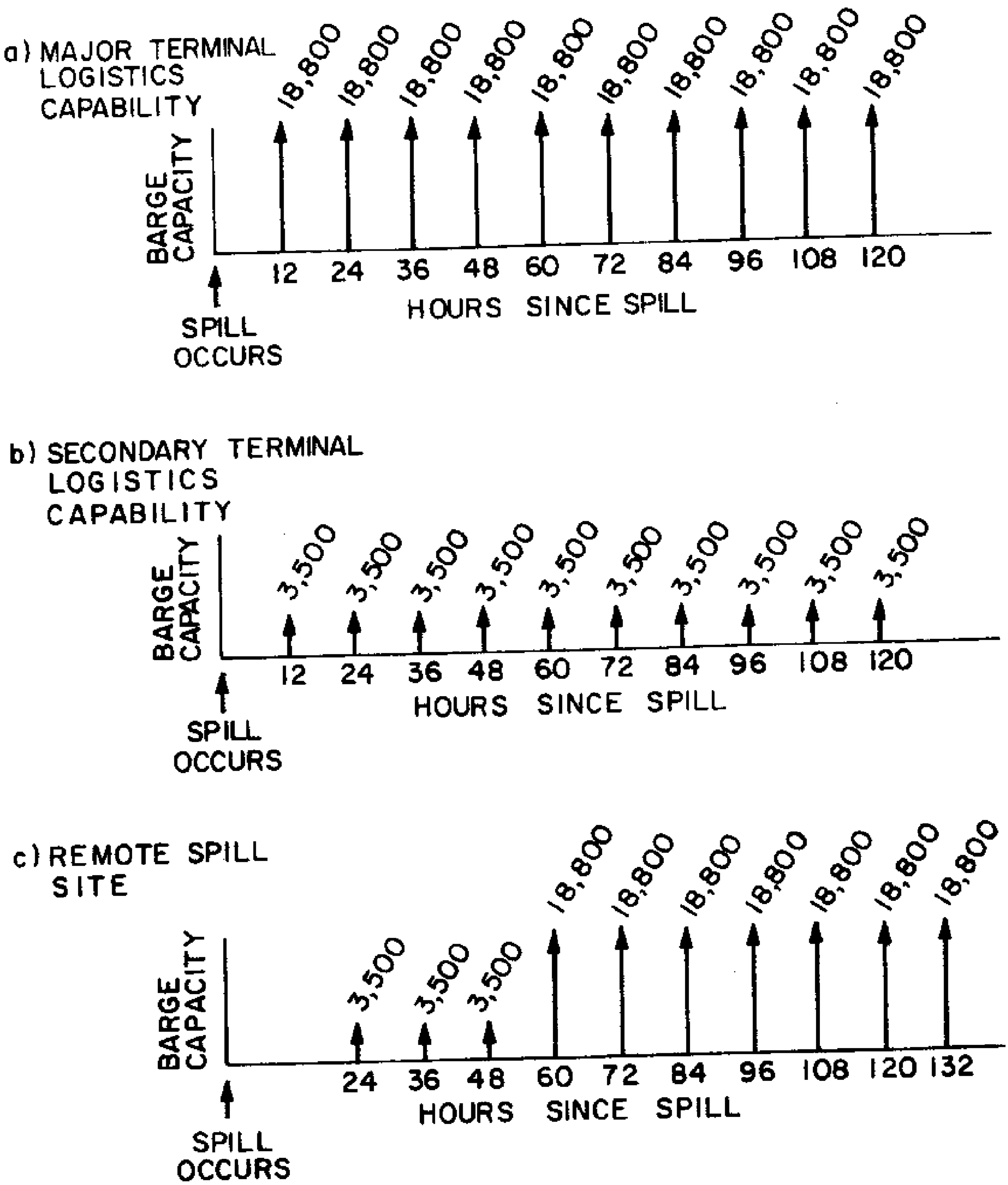

a) MAJOR TERMINAL LOGISTICS CAPABILITY
BARGE CAPACITY
18,800 18,800 18,800 18,800 18,800 18,800 18,800 18,800 18,800 18,800
12 24 36 48 60 72 84 96 108 120
HOURS SINCE SPILL
SPILL OCCURS
b) SECONDARY TERMINAL LOGISTICS CAPABILITY
BARGE CAPACITY
3,500 3,500 3,500 3,500 3,500 3,500 3,500 3,500 3,500 3,500
12 24 36 48 60 72 84 96 108 120
HOURS SINCE SPILL
SPILL OCCURS
c) REMOTE SPILL SITE
BARGE CAPACITY
3,500 3,500 3,500
18,800 18,800 18,800 18,800 18,800 18,800 18,800
24 36 48 60 72 84 96 108 120 132
HOURS SINCE SPILL
SPILL OCCURS

FIGURE II-3-9

$$\frac{dV_B}{dt} = \begin{cases} 0; \text{ if } V_B = V_{BCAP} \text{ and } & R - N_sQ - n_BV_B \geq 0 \\ \text{else:} \\ R - \eta_sQ - \eta_BV_B; \end{cases} \quad (25)$$

where V_{BCAP} = maximum capacity of the boom in gallons; R = spillage rate in gph; η_s = skimmer efficiency measured in terms of vol. oil/(vol. oil + vol. water) retrieval (presumed to be .9); η_B = boom efficiency, measured in vol. lost through leakage in 1 hour divided by volume contained, presumed here to be .05; and Q is the rate at which the skimmer, when working under ideal conditions, can pump the oil. Q will be one of two values. If the depth of the oil contained in the pool is less than the critical depth required for subcritical flow over the weir then equation (24) specifies Q. If the depth of the pool is sufficient to feed the skimmer at its design pumping rate, then Q is just given by this design pumping rate.

The rate of change of the volume of oil lost is then given by:

$$\frac{dV_L}{dt} = \begin{cases} R - \eta_sQ; \text{ if } V_B = V_{BCAP} \\ \eta_BV_B; \text{ if } V_B < V_{BCAP} \end{cases} \quad (26)$$

These equations could be simply solved except for the awkward dependence of Q on V_B(see equation (24)). Moreover, the process is not really continuous, as we can see by the alternate forms available for specifying the rates. For certain complicated barge arrival schemes, the process might be switching from one behavior to another quite frequently.

Consequently, a finite step approximation was developed for the rate equations and this was incorporated into a computer simulation. This simulation recreates the time history of a spill given the boom capacity, skimmer pump rate, weir depth, skimmer and boom efficiencies, volume spilled, rate of spillage, barge arrival pattern, and the boom deployment time.

Figure II.3.10 depicts the history of a 10 million gallon spill in a major oil-handling terminal presuming a high rate of spillage of 500,000 gph and a maximum skimmer pumping rate of 60,000 gph. Note that the principal losses come from the inability of the skimmer to retrieve the oil as fast as it is being spilled. The boom filled up rapidly. Its leakage was not significant compared to the losses incurred by the spillage rate. Moreover, choked or critical flow played no role in the incident, as the critical boom capacity was 66,000 gallons, and the volume in the boom was almost always in excess of this value.

The spill simulation was run once again, but now for a slower spillage rate, one of 100,000 gph. This is depicted in Figure II.3.11. Note that the boom never fills up; this is due to the leakage. Again, the problem of critical flow is never important. Approximately half the oil was recovered. This may be explained by noting that the retrieval rate was about one-half that of the spillage rate. Based on these two cases, it can be seen that the retrieval rate appears to be one of the key parameters in specifying cleanup effectiveness.

Figures II.3.12 through II.3.14 depict the amount of oil lost from a 10 million gallon spill as a function of the capacity of the boom initially deployed for the three harbor types. The high and low spillage rates are shown. Note that the effect of going to a larger boom is not so important with slow spills, but that efforts to retrieve rapidly occurring spills are greatly enhanced by utilizing larger booms. This is particularly true for the remote spill site. Of course, 80 or 90% of the oil is still lost. To make significant inroads in this spillage would require either very much larger booms, or much higher retrieval rates, coupled with early barge arrivals.

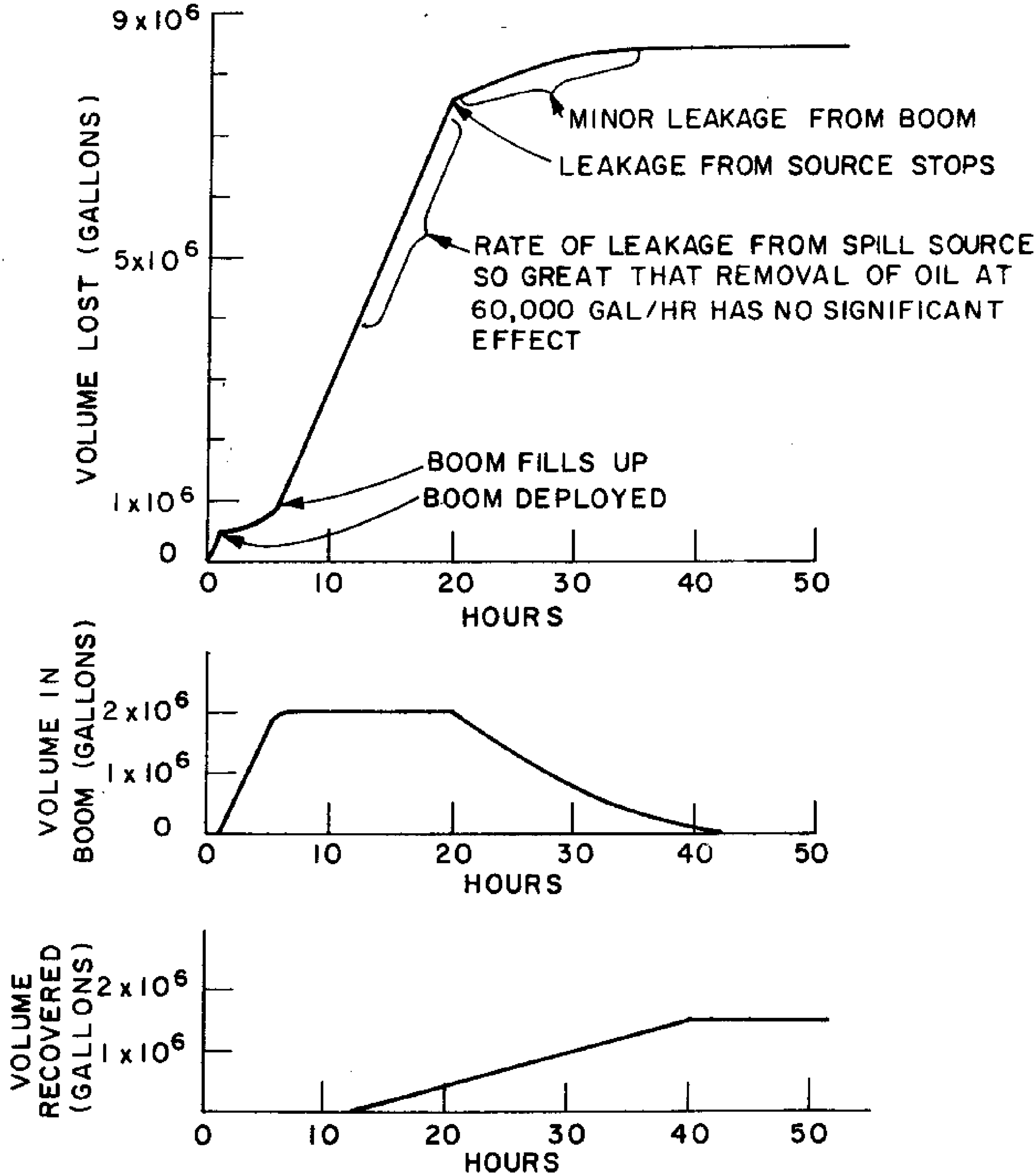


FIGURE II -3-10 TIME HISTORY OF HYPOTHETICAL 10 MILLION GALLON SPILL

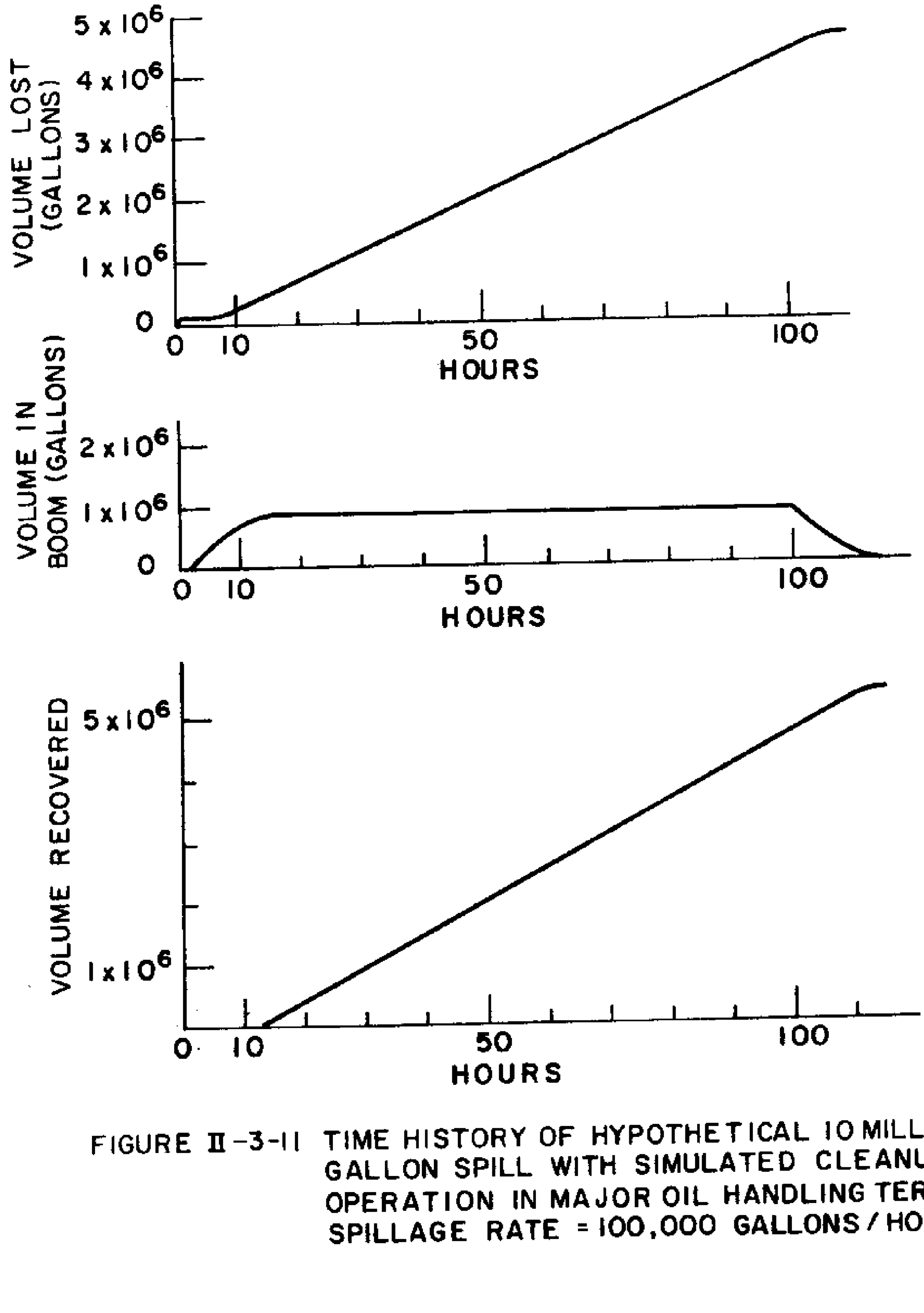


FIGURE II-3-11 TIME HISTORY OF HYPOTHETICAL 10 MILLION GALLON SPILL WITH SIMULATED CLEANUP OPERATION IN MAJOR OIL HANDLING TERMINAL SPILLAGE RATE = 100,000 GALLONS / HOUR

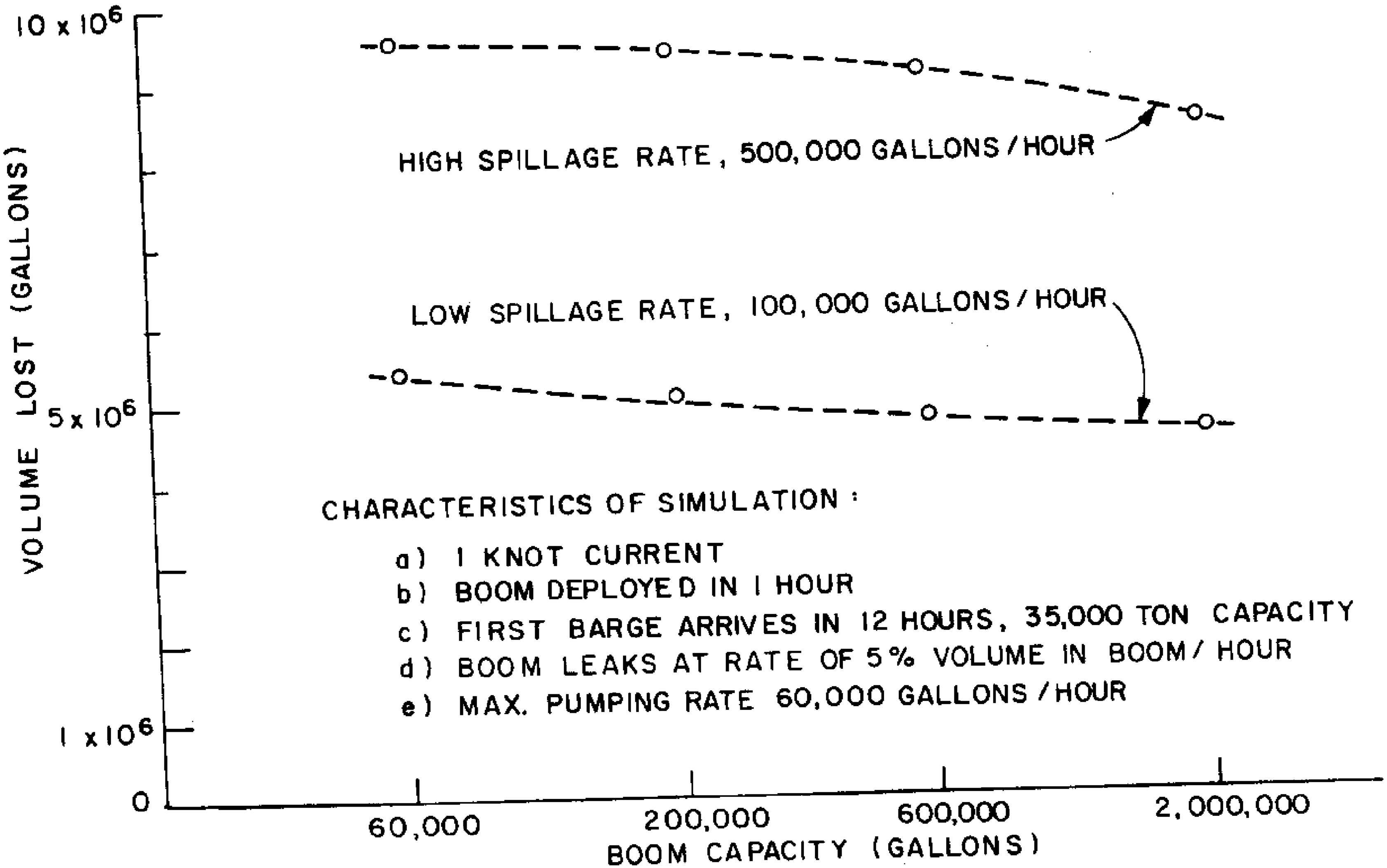


FIGURE II-3-12 VOLUME OF OIL LOST VERSUS BOOM CAPACITY FOR SIMULATED 10 MILLION GALLON SPILL AT MAJOR OIL HANDLING TERMINAL

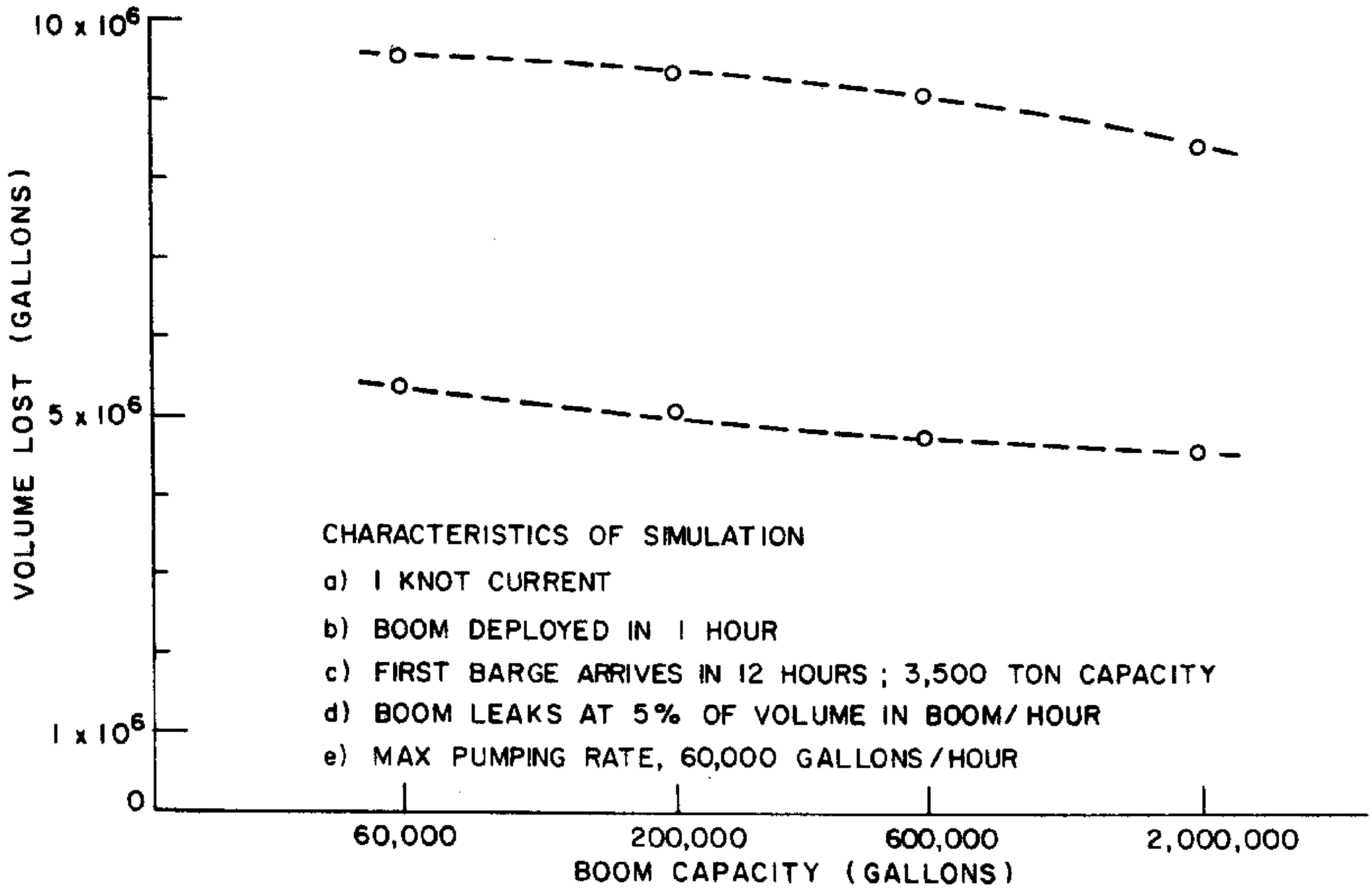


FIGURE II-3-13 VOLUME OF OIL LOST VERSUS BOOM CAPACITY FOR SIMULATED 10 MILLION GALLON SPILL INCIDENT AT SECONDARY OIL HANDLING TERMINAL

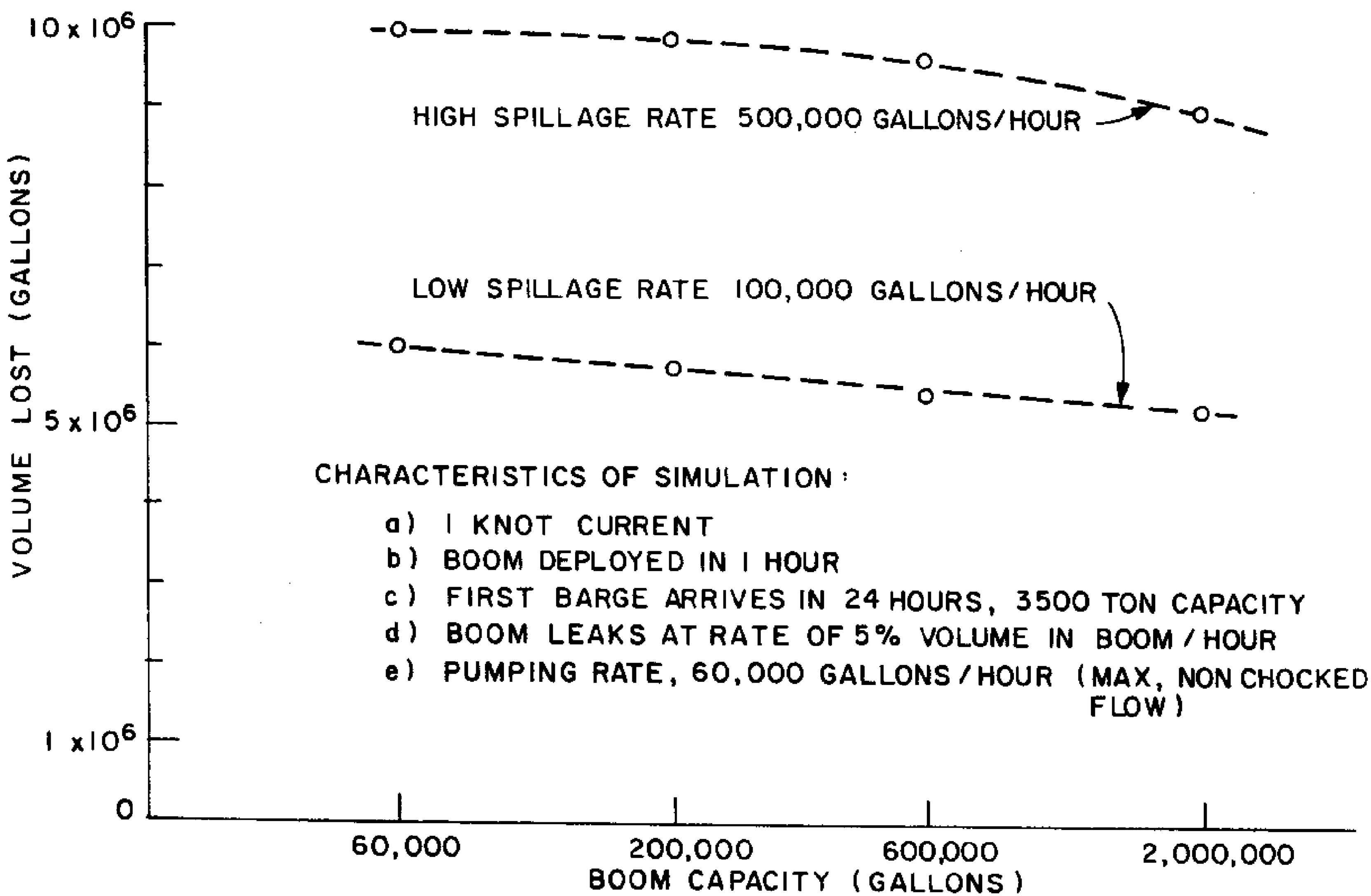


FIGURE II-3-14 VOLUME OF OIL LOST VERSUS BOOM CAPACITY FOR SIMULATED 10 MILLION GALLON SPILL INCIDENT AT REMOTE SITE

II.3.7 Summary

Oil spill clean-up is a multifaceted problem. In the one example we have discussed, it was apparent that for very large spills the principle parameter dictating the operation's effectiveness was the ratio of retrieval rate to spillage rate. It is apparent that the types of skimmer now available are probably much too small to handle either of the hypothesized spillage rates and volumes. This points out the necessity for carrying out a study of this sort for a range of spill scenarios covering the possibilities inherent with any particular port or terminal plan. The problem is complicated enough to negate any prior feelings we might have with respect to the adequacies of our preparation.

Additional costs that must be considered in doing such a detailed study are those associated with the two or three workboats required to manipulate the boom, skimmer and barge; and post-deployment maintenance and restoration of equipment.

Attempts to contain a spill on the Georges Bank appear to be at best a marginally feasible, extremely expensive proposition, probably a waste of resources. This fact, combined with the importance of the nearshore spill (Chapter II.1) and regional income impact (Chapter I.7) and perhaps also biological impact (Chapter II.5) makes the nearshore spill the proper focus of collection and containment efforts.

It appears that a properly designed, rapidly deployed (boom, skimmer, and barge) system could recover a significant portion and in many cases the bulk of most spills occurring in protected, nearshore waters. If we presume that the maximum spill rate is 100,000 gallons per hour, and the largest spill is on the order of 10,000,000 gallons, then a system having the following characteristics should prove to be better than 75% effective in recovering spilled oil in protected waters.

a) Initial containment and subsequent skimmer collection to be provided by a boom having a capacity in the range of 1 million gallons, and a deployment time on the order of 1 hour.

b) Skimmer to have a maximum pumping ratio of 100,000 gallons per hour and a deployment time of under 5 hours.

c) Barges to be provided within five hours of notification.

Tradeoffs are possible within this framework. For example, slower barge delivery or decreased skimmer pumping capacity could be counterbalanced in part by larger boom capacities.

A spill simulation utilizing two-hour skimmer and barge deployment and one-hour boom deployment indicated that better than 85% recovery could be anticipated for booms ranging in size from 60,000 gallons and up, provided the skimmer pumping capacity is about 100,000 gallons per hour. Such a system is feasible, although in total it represents a very large improvement over presently deployed systems. The boom may be readily procured, and its cost should fall in the range of $10,000 to $50,000. The skimmer is unusually large, but power and size requirements are still modest in comparison to other types of marine equipment. It would almost certainly cost less than $250,000. Finally, barges could either be procured, or contractual agreements could be reached with the products distributors in New England to provide barges on notification. The annual cost of such an agreement would be directly related to the decreased utilization of the distributor's barges. This would be related in turn to the required deployment capability, and the specifics of the offloading and transshipment process. The deployment time constraints are impossible to meet unless a complete system is permanently available in the port being protected. This implies that 3 or 4 such systems might be required for New England. The total initial cost of such a regional operation would lie somewhere in the neighborhood of several million dollars. If this system was staffed by special-purpose personnel, the present value of annual costs could be several times this figure. If refinery or equivalent people were used on an as-needed basis, the annual regional cost would be cut considerably. In any event, comparing these numbers with those of Table I.7.2, which estimates the regional costs of nearshore spills, it is clear that the provision of nearshore spill collection system merits very careful analysis, whatever New England's future petroleum system.

Chapter II.4
Background Information on Biological Effects of Oil Spills and Discharges

II.4.1 Objectives and scope

The objectives of Chapters II.4 and II.5 are to attempt to assess as clearly as possible the biological consequences of various hypothetical events relating to development of New England offshore petroleum discoveries and refinery location. The geographical region studied consists of the Gulf of Maine and New England coastline from Eastport to Block Island. The results of the study are based on the current "state-of-the-art" with regard to our understanding of the biological response to environmental changes of interest and the ability to predict the actual consequences of such events for the region considered. In this context then, our study is primarily a review and interpretation of the literature. No primary data collection has been undertaken.

Chapter II.4 presents the necessary background information. The data base and basic assumptions upon which the conclusions in Chapter II.5 are made are developed. Section II.4.2 is a description of the existing conditions in the study area. The composition and properties of oil are discussed in Section II.4.3, especially as these relate to impacts on marine biota. The available data on specific biological effects of oil by species are summarized and presented in Section II.4.

Chapter II.5 is an interpretation of the basic information developed in II.4 relative to a specific set of hypothetical events. Also, we attempt to provide a basic framework for including new information as it becomes available.

II.4.2 Description of existing conditions

II.4.2.1 Gulf of Maine (including Georges Bank)

Physiography/Hydrography.--The following paragraphs provide a brief sketch of many of the factors which influence the environment in the Gulf of Maine, especially those which are of importance in the maintenance of a stable ecosystem.

The body of water over the continental shelf bounded on the east and west by longitudes 65°30'W and 71°W respectively (see Figure II.4.1) and by the 1,000 fathom contour on the south, has been called the "Gulf of Maine" since the end of the last century (Bigelow, 1927). Its boundaries are more obvious beneath the sea's surface, where a series of shallow banks to the east and south separate a deep inner basin from the continental slope (Figure II.4.1).

The coastline is marked by two easily recognizable landform types: continuously rocky shores northeast of Cape Elizabeth (just south of Portland), and sand beaches south of Plymouth. The stretch between is characterized by a mixture of the two types, Cape Ann being the most prominent rocky headland in the interval.

Bigelow (1927) defined the 50 fathom contour as the boundary between the banks and the basins which together characterize the bottom topography of the shelf. The Eastern Channel, about 140 fathoms deep, divides Georges Bank from Browns Bank to the north, and leads into the Y-shaped central basin of the gulf, one arm of which extends toward Cape Ann, the other toward the eastern section of the coast of Maine. The gulf is deepest just inside the Eastern Channel at the base of the steep northern slope of Georges Bank, where the depth is usually greater than 150 fathoms. A smaller deep basin of comparable depth is located east of Cape Ann, at the inshore end of the western branch of the "Y". In general, the

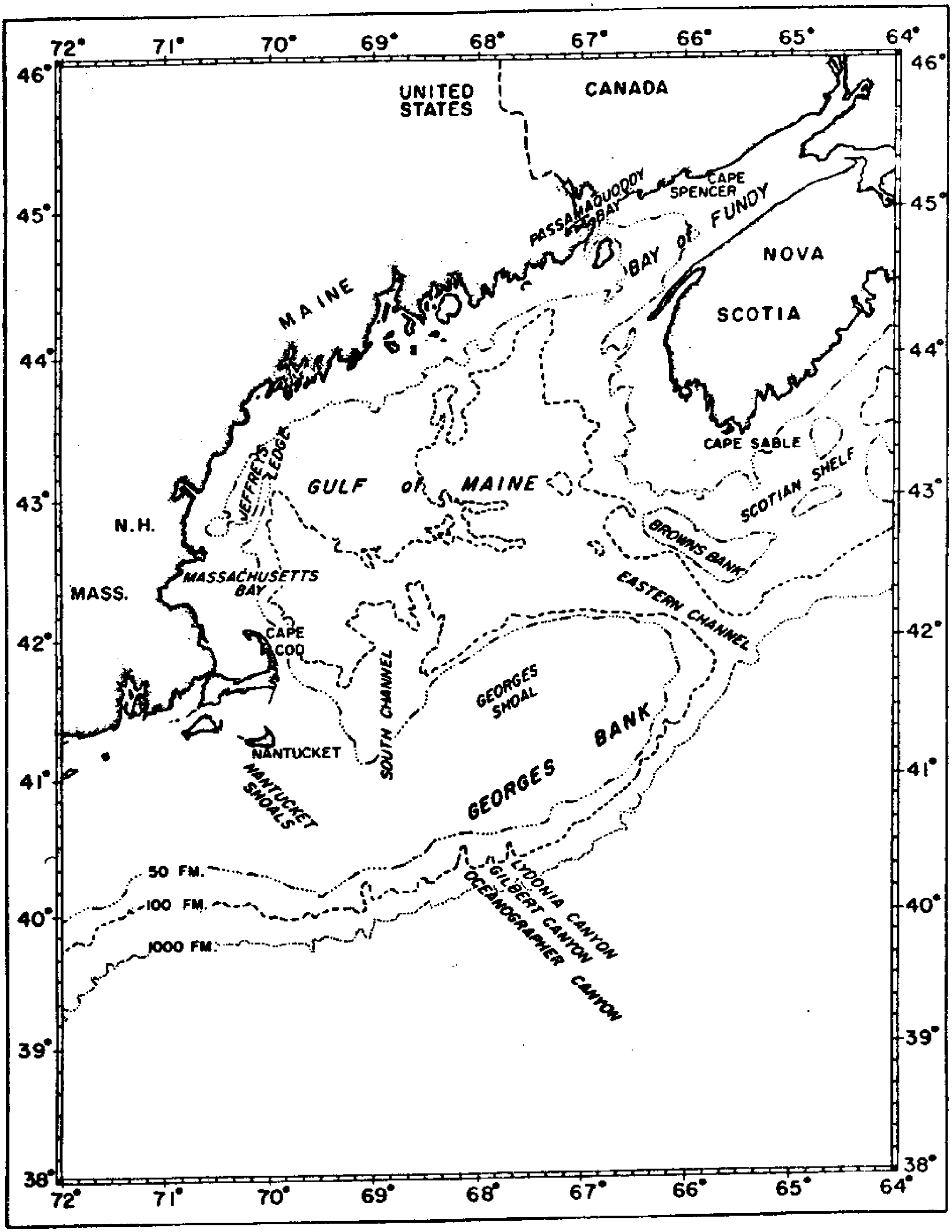


Figure II.4.1

Orientation chart of the Gulf of Maine.(Colton,1964) depth of the floor in both branches averages about 125 fathoms. A series of smaller banks stretching in an arc from Nova Scotia to Cape Cod form the "lip" of the basin, separating the deeper basin of the gulf from the continental slope and the abyssal plain beyond it.

Georges Bank is part of the terminal moraine that was left after the Wisconsin stage glaciers of the Pleistocene Epoch retreated about 15,000 years ago. A moraine is a deposit of boulders, gravel, and sand that was left as the leading edge of a glacier melted, while the production source of the ice (in the Arctic) precisely kept pace with the rate of melting. As the ice travelled down, it scraped against everything in its path, scooping up tons of loose rock. Thus, a conveyor belt type of mechanism evolved, moving tons of rock south, and dropping it at the melting edge of the glacier (Strahler, 1966).

The basin behind the bank was protected from wave action by it as the sea rose. Thus, fine glacial sediments (mostly silt particles smaller than 0.1 mm) are still present in these basins. Tidal scouring, erosion from melting glacial waters, and wave action all combined to strip Georges Bank of its fine sediment - at least at the sediment surface. The surface stratum is now mostly coarse sand. Interspersed are areas of gravel (Wigley, 1961) which are known to be the spawning grounds of many important species of fish.

The Gulf of Maine is on the order of three parts per hundred less saline than the slope and Gulf Stream waters (35 0/00) a few miles to the east. The effects of land runoff exert the greatest influence on the salinity of the gulf. Nine major rivers account for 5/6 of the 61,300 sq. mi. of watershed which drains into the gulf. Bigelow (1927) reviewed salinity data for several locations around the gulf and found in general that near the coast, surface salinity was reduced in proportion to the amount of nearby land runoff. As depth increased, this dilution effect was usually found to decrease. This salinity difference between surface and bottom was observed to be greatest during the spring freshening and least during autumn and winter, when the most vigorous mixing occurs, and little drainage flows into the gulf.

Water temperatures in the Gulf of Maine are regulated primarily by its location downwind of a rigorous land climate. The sea temperature follows the temperature of the air blowing off the continent to the west. Bigelow (1927) maintains that there is little effect produced by cold "Arctic" currents coming down the east shore of Nova Scotia or by river water mixing with the sea. Solar radiation induces surface warming, which propagates, depending on the strength of vertical circulation down to the deeper layers.

In the spring, solar radiation and air warm the surface water, causing a layer of less dense water to form over a cold deeper layer. This stratification inhibits vertical mixing, and frequently, dissolved oxygen may become depleted in the deep layers. During fall, this stratification breaks down, depending on the difference between air and water temperature, tidal and wind-induced mixing, and currents.

Offshore water biology.--The waters north and south of Cape Cod have markedly different thermal regimes, resulting in substantial differences in biotic distribution. The *American* Atlantic Boreal Region extends from Cape Cod north to the coast of Labrador. It is populated by many species that are typical of the European Boreal Region, which is a biogeographical unit extending from the English Channel to the North Cape of Norway. Sixty to eighty percent of the forms in such unrelated taxa as laminarian seaweeds, mollusks, various crustacean orders, and teleost fish are common to both the eastern and western Atlantic. South of Cape Cod, in the Virginian Province, the proportion of species shared with northern Europe is about 7 or 8%. Boreal species ranging south of the Cape tend to be local or scarce or they are confined to deeper waters. Boreal plankters south of Cape Cod usually appear only during the cooler seasons.

The categorization of animal distributions as Boreal or Temperate is useful as a shorthand notation of geographic range. The distribution of animals in terms of communities reflects the species relation to the environment in a more intimate sense. Of particular interest is the pelagic community which characterizes the water column in the gulf, inshore waters, and its banks and the benthic communities which may be intertidal (coastal) or sub-tidal (including Georges Bank).

Pelagic plants and animals live within the water column. Pelagic animals are either planktonic or nektonic, depending on whether they float freely and more or less passively in the plankton or propel themselves actively as members of the nekton. The principal distinction is the plankter's inability to alter its distribution in any wide geographic sense; it goes where it is carried. Few invertebrates except squids qualify as nekton. Some, such as prawns and shrimp, nereid worms, portunid crabs, jellyfish, and others, swim for short distances but have a limited capacity for migration compared to fishes or marine mammals.

Microscopic plants in the phytoplankton, diatoms and flagellates mostly, are at the base of marine food pyramids. The contribution of macroscopic algae and marine seed plants to primary production in the ocean is insignificant by comparison. Herbivores in the zooplankton, notably calanoid copepods, graze on these microscopic pelagic plants and are eaten in turn by carnivorous planktons, including comb-jellies, arrow worms, and jellyfish, and by herring, menhaden, mackerel, and other filter-feeding fish. Both plant and animal planktons which settle out of the water column are food for a host of benthic (bottom-dwelling) animals including bivalved mollusks, barnacles, bryozoans, worms, amphipods, hydroids, jellyfish, and sponges.

Plankton composition follows an annual cycle. Inorganic nutrients (nitrates and phosphates) accumulate in the water during winter, since little phytoplankton photosynthesis takes place because of low light and temperature levels. In the absence of their phytoplankton food, herbivorous zooplankton are also scarce. During late winter and early spring, a daylight length increase and water temperature rise, a "bloom" of phytoplankton occurs, usually composed mostly of one species. This bloom quickly dies off and is eaten by zooplankton, and other phytoplankton species begin to multiply, although at a much slower rate than that characteristic of the initial bloom. Near the end of the summer, a subgroup of phytoplankton known as dinoflagellates begins to increase in number. Some species of dinoflagellates, which have red rather than green photosynthetic pigments, occasionally bloom, if temperature, salinity, and nutrient conditions are right. This is the poisonous "Red Tide" which struck New England in 1972.

Species composition of the zooplankton changes seasonally, but at all seasons copepods are usually the most important. These, in turn, sustain predator populations including comb jellies, arrow worms, crustacean larvae, hydromedusae, and larger jellyfish. During the summer the larvae of benthic organisms and finfish make a significant contribution to the total zooplankton, attaining values of the order of 50,000 to 100,000 individuals per cubic meter. It should be noted that, with very few exceptions, the larval forms of benthic organisms and finfish exist during this sensitive period of their life cycle at or immediately below the surface.

The cyclic pattern briefly outlined above is one of the chief traits of the plankton on this coast. Frequently the broad pattern is bimodal with renewed peaks of both phyto- and zooplankton in the fall of the year.

Among the more important pelagic finfish indigenous to the Gulf of Maine are the cod, haddock, herring, whiting, pollock, cusk, dab, and ocean perch. Mackerel, tuna, menhaden and striped bass are among the important non-indigenous fish. There are many other smaller fish which play important, intermediate roles in the food chain.

With few exceptions, the indigenous fish of this zone are bottom-dwellers or lower pelagic during the adult period of their life cycle. (Exceptions are the herring and pollack). Also, with few exceptions, the eggs of these species are buoyant (exceptions are the herring, blackback and flounder and alewife) and float at or near the surface for a period of from 10 to 30 days during incubation after emission. The larval stages of these fish are, with no significant exceptions, buoyant, and are free-floating at or near the surface during the larval period, which generally ranges from 2 to 4 months, depending on temperature.

The spawning areas of the Gulf of Maine are widely distributed offshore and inshore, and there is a specific relationship between these locations and the nursery grounds. As the circulation of surface water is generally counterclockwise in the Gulf of Maine, the eggs released at sea on the Georges Bank and other important spawning beds in the Gulf of Maine drift either seaward to the east and are lost, or toward shore and the inshore estuarial areas, which are open to tidal flow, and certain current-trapping or eddy-inducing bodies such as Ipswich Bay, and Cape Cod Bay, assume great importance as maturation areas. Those species with most specific spawning areas are the haddock, which spawns over gravelly areas on the Georges Bank, and the cod, which spawns in Cape Cod Bay off Plymouth, Massachusetts, north of Cape Ann in Ipswich Bay, the eastern part of Georges Bank, and Browns Bank. The herring spawns throughout the region, with concentrations off Cape Sable and the mouth of the Bay of Fundy. (See Figure II.4.2.)

Table II.4.1 and Figure II.4.3 summarize the seasonal variation in fish spawning. Most finfish have rather well defined spawning seasons which are triggered by rising or falling temperatures. Spawning and larval development occur within a particular temperature range (and to a lesser extent salinity). Although most species spawn during the rising spring temperatures, there is some spawning activity nearly year-round. Female fish typically release 500,000 - 1,000,000 eggs per year for the larger species and 30,000 - 50,000 eggs per year for the smaller flounder and herring.

There is little specificity in feeding during the early life of the fish of this area. During the larval stages, when living at or near the surface, most species depend upon copepods, minute crustacea, larval shrimp, eggs and larvae of all kinds, diatoms and almost any minute form of life which is available. Upon reaching the post-larval stage and settling to the bottom or assuming the lower pelagic life, the species become somewhat more specific, but there is a wide range of food and prey available, the only differentiation being caused by size, speed, and location. The range of foods for almost all species includes any smaller fish, copepods, pelagic shrimp of all kinds, shrimp-like euphausiids, crustacea, sea urchins, sand dollars, brittle stars, crabs of all species, mollusks, the many species of worms, ascidians, amphipods, appendicularians, ctenophores, squid, peridians, snails, decapod crustaceans, and many others.

The benthic community consists of the bottom-dwelling organisms. Wigley (1961) has reported on a survey of benthic fauna on the Georges Bank. Striking correlations were observed between the type of bottom sediment and the quantity of benthic organisms. High abundance was associated with coarse sediments, and low abundance was associated with fine sediments. By far the greatest faunal weight was found in gravel and sandy gravel bottoms. The biomass in the sandy gravel sediment was exceptionally high 1300 gr/m^2), due largely to the occurrence of dense beds of *Modiolus modiolus*, the northern horse mussel. Low quantities occurred in sediments in which the sand fraction was dominant. Lowest weights were found in clayey silt and silty clay bottoms.

The relation of numbers of specimens to sediment classes was quite similar to that for weight. Greatest numbers of specimens were found in gravels and sands; fewest specimens occurred in sediments containing large

TABLE II.4.1

SPECIES	SPAWN SEASON RANGE	SPAWN SEASON MAX	SPAWN TEMP. °F	SPAWNING AREA
Silver Hake (Whiting)	June-Oct.	July, Aug.	50-60	Coastal (< 50 Fathoms) Cape Cod to Grand Manan
Cod	Nov.-April	variable	41-47	Coastal and on Georges Bank (see Figure II.4.2)
Haddock	Feb.-May	April	40°	Primarily on Georges Bank some coastal (see Figure II.4.2)
Pollack	Nov.-Feb.	Dec., Jan.	40-45	Mouth of Mass Bay and eastern slope of Stellwagen Bank (< 50 Fathoms)
White Hake/ Red Hake	Feb.-June	?	?	Coastal (not well known)
Halibut	April-Sept.	April-May ?	40-45	No distinct areas; throughout the Gulf of Maine
American Dab	March-June	April-May	?	No distinct areas; throughout the Gulf of Maine
Summer Flounder	(not well known)			No distinct areas; throughout the Gulf of Maine (possibly greatest on southern slope of Georges)
Winter Flounder	Jan.-May	Feb.-March	32-37	No distinct areas; throughout the Gulf of Maine
Herring	Aug.-Nov.	Sept, Oct.	46-52	Bay of Fundy; Maine Coast; possibly on Bunk in same region as Haddock

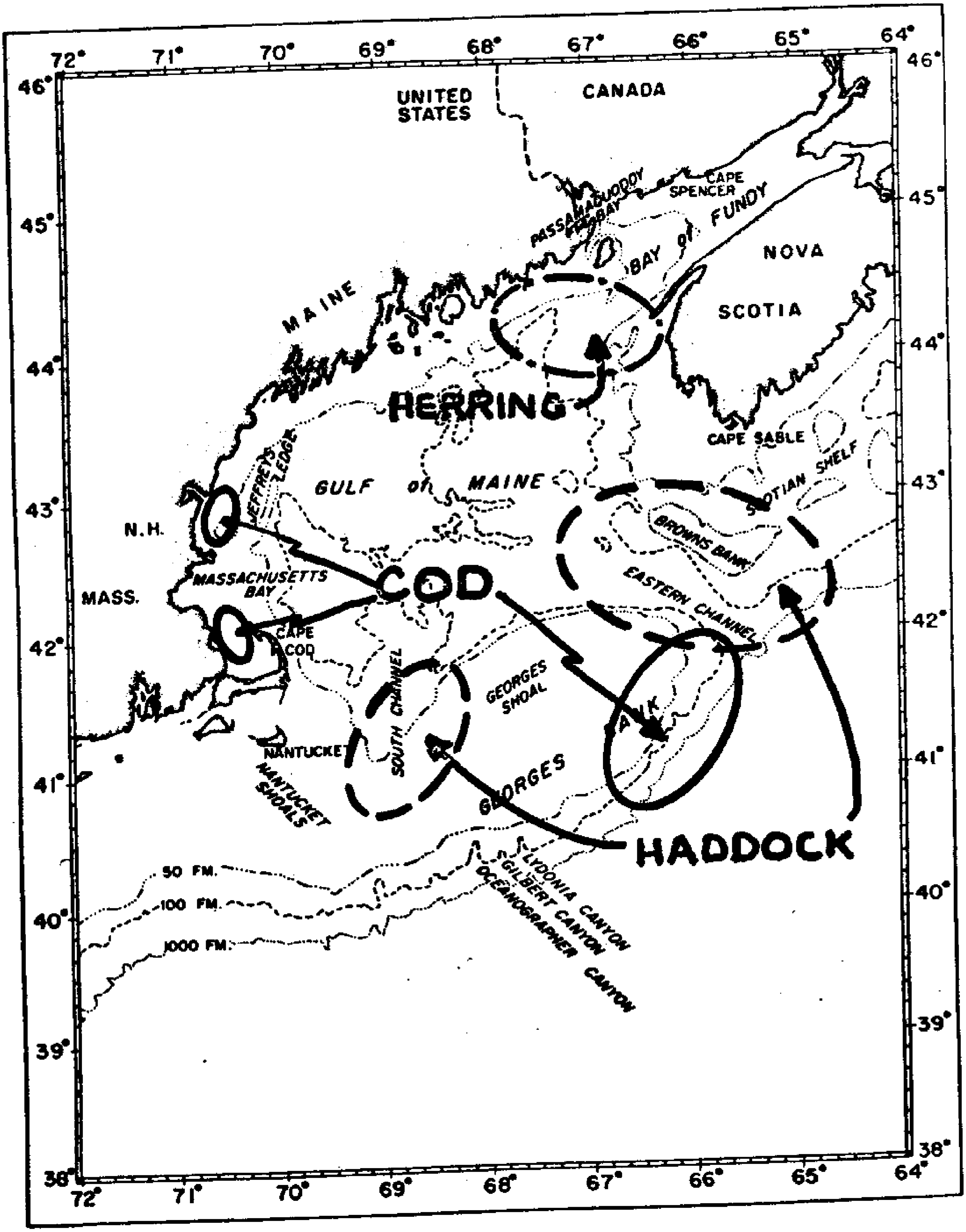
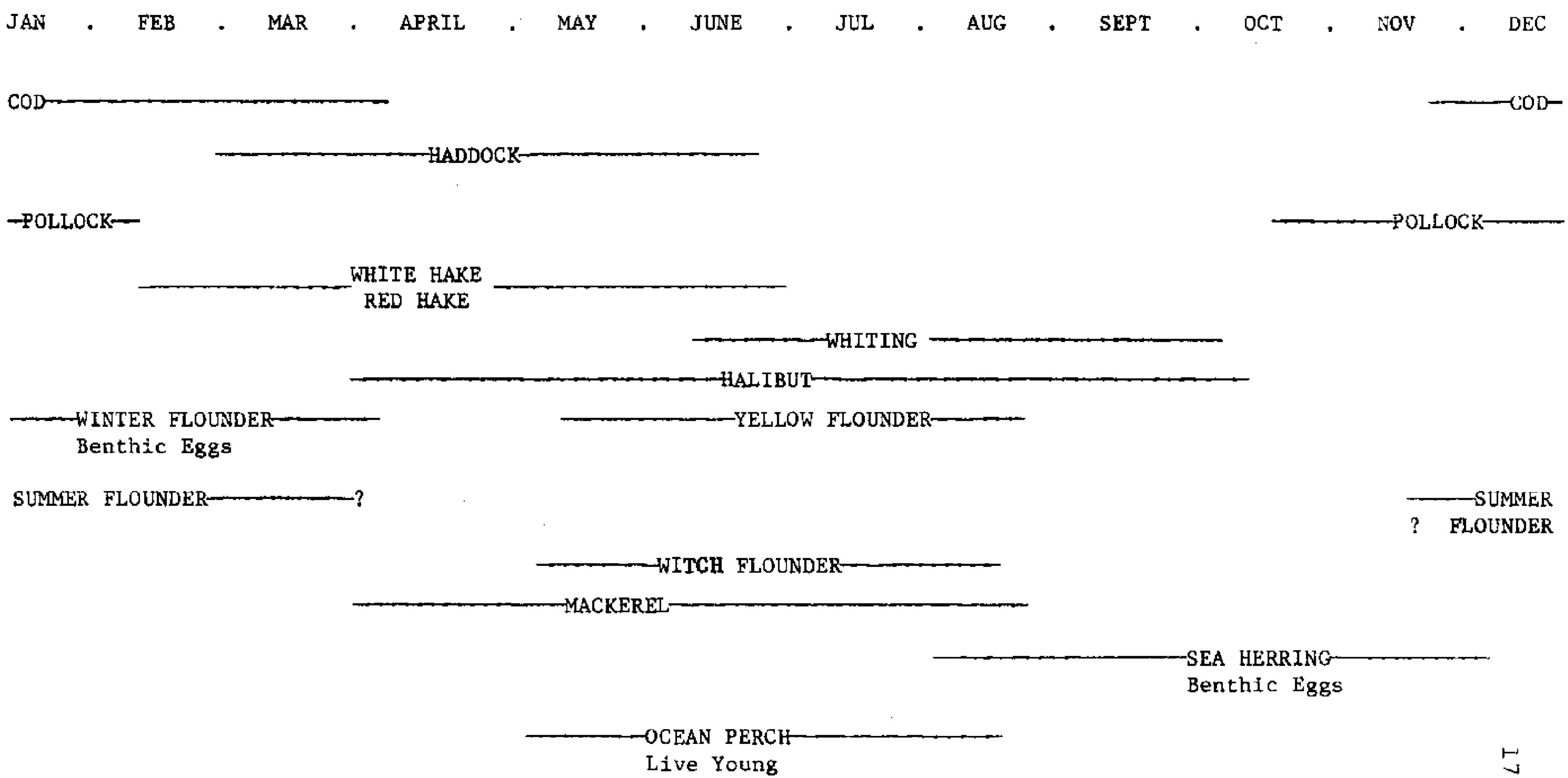


Figure II.4.2

Major spawning grounds in the Gulf of Maine.

FIGURE II.4.3

SPAWNING SEASONS-GULF OF MAINE FISH

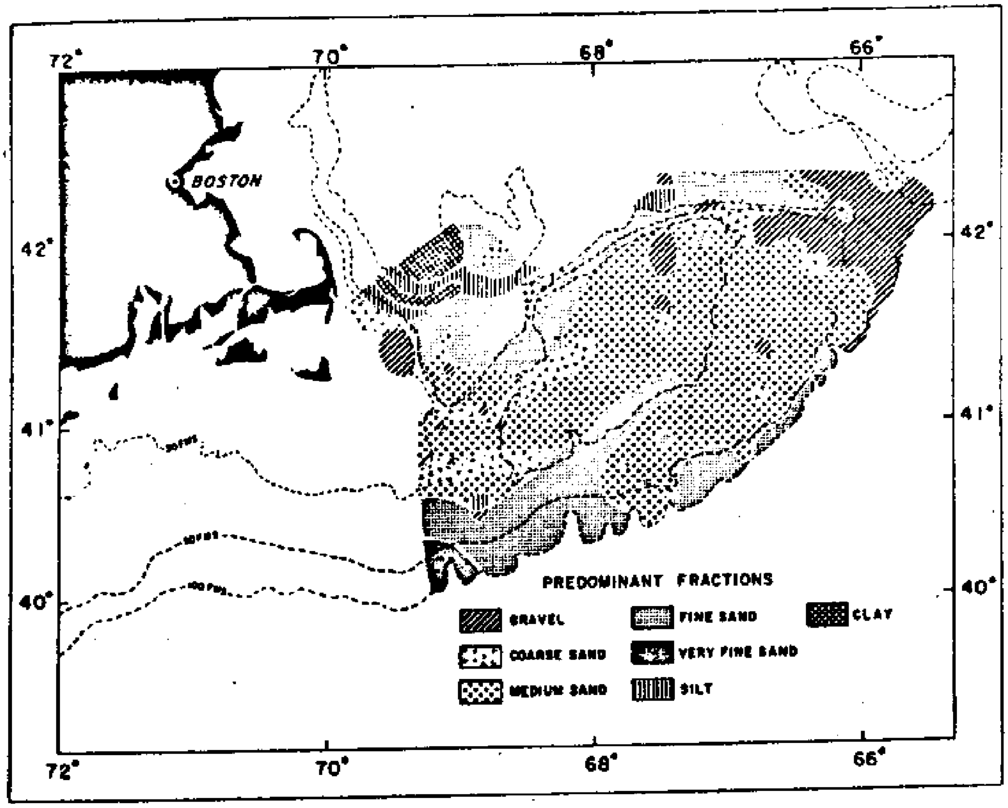


quantities of silt and clay. Organisms were most abundant ($1,934/m^2$) in the sand textural class. Gravel, sandy gravel, and gravely sand also rank high, with the number of specimens ranging from 1,513 to $1,718/m^2$. Except for the clayey sand category, in which the number of specimens averaged $1,074/m^2$, the remaining textural classes (silty sand, sand-silt clay, sandy silt, clayey silt, and silty clay) supported few specimens - 255 to $436/m^2$.

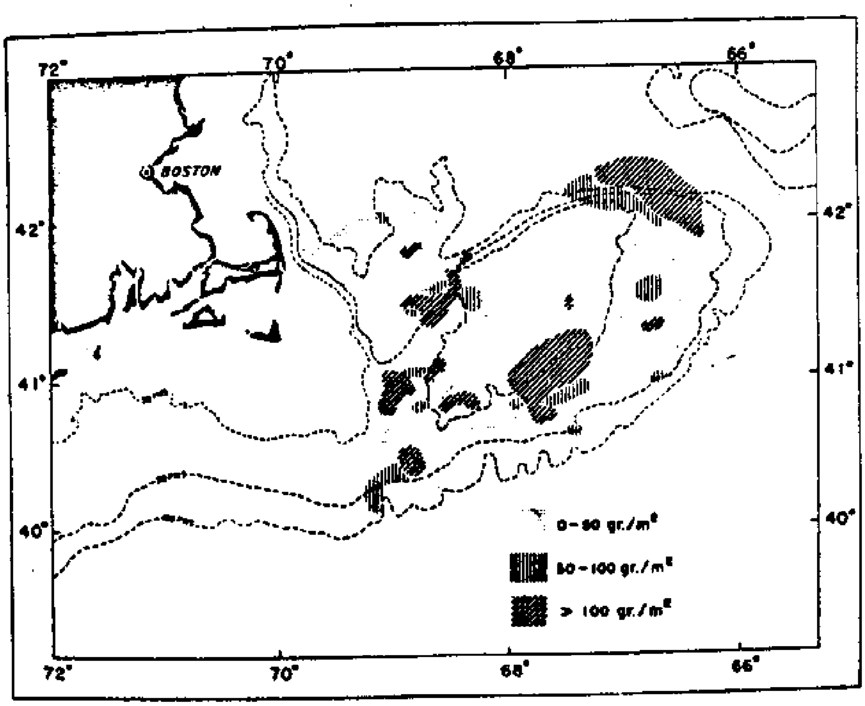
There were three areas of the Bank where a high density (> 100 $gr./m^2$) of benthic animals occurred; the northeast, south-central, and western. The first two of these areas each consist essentially of one large contiguous area, whereas the third is a cluster of six relatively small high-density patches. Figure II.4.4 indicates the correspondence between benthic biomass and sediment distribution.

Each major faunal component has a somewhat different and distinct geographic density pattern. Crustaceans are most prevalent along the western and southeastern parts of the bank; moderate quantities occur in the northeast and southern sections. Mollusca are most abundant on the northeast, south-central, and western portions. Echinoderms are especially dense in the central portion, with moderate quantities occurring on the bank's northeast, south-central, and western portions. Annelids are prevalent on the northeast, south-central, and western sections. Annelida are the only group abundant in Georges Basin, the deep-water area northwest of Georges Bank. The benthic fauna of the bank are composed by weight of the following groups: molluscs 41%, echinoderms 31%, miscellaneous groups 17%, annelids 6%, and crustaceans 5%.

Of particular interest is the distribution and migration of offshore stocks of lobster (_Homarus americanus_). Tagging experiments (Cooper and Uzmann, 1971) have revealed



(a)
Geographic distribution of sediment fractions.



(b)

Geographic distribution of benthos.

Figure II.4.4 (from Wigley,1961)

that two stocks exist in the Gulf of Maine. One is not migratory and remains in coastal waters year-round. The other undergoes extensive seasonal migrations. These lobsters maintain a higher growth rate than the coastal population.

The offshore population is found on the edge of the continental shelf (the southern and southwestern edges of Georges Bank) to depths of 700 m. They move into warmer coastal waters (often travelling hundreds of miles) in late spring and early summer to spawn. The time of migration is correlated with bottom temperature on the bank being not high enough to permit spawning in summer. The lobsters migrate out to deeper water in late fall and early winter completing the yearly cycle. Figure II.4.5 indicates the migratory pattern of this population.

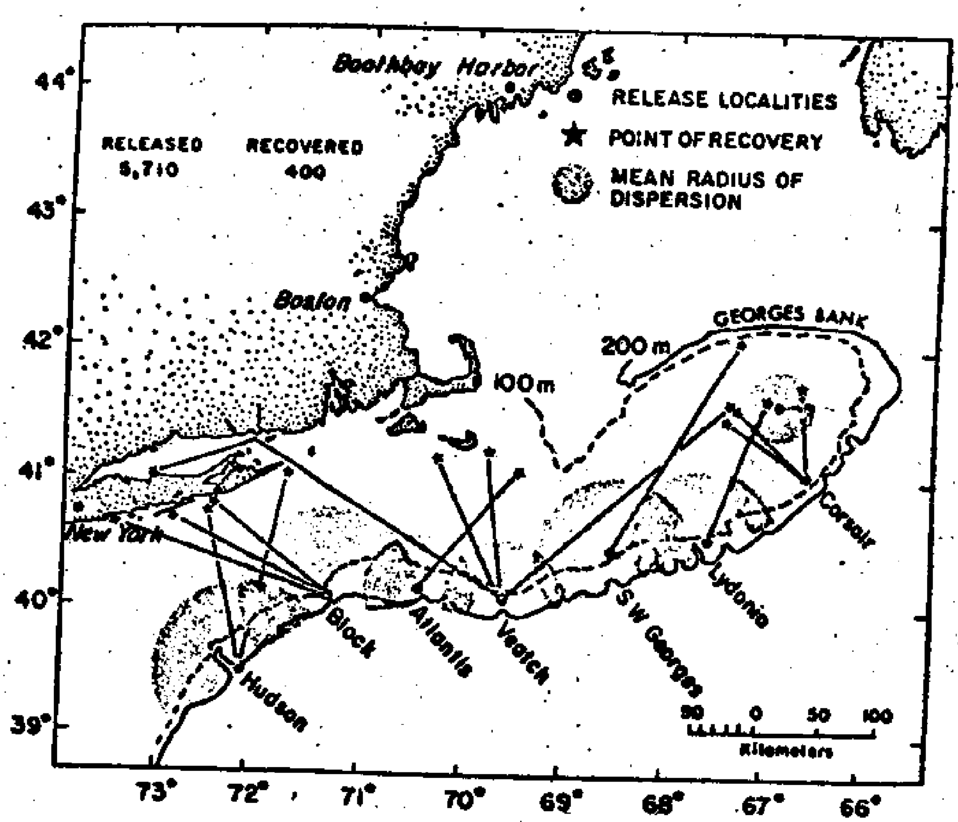


Figure II.4.5
Dipersion of tagged lobsters.(Cooper and Uzmann,1971)

The pelagic and benthic blooms of the Gulf of Maine are strongly coupled by the many finfish which feed on the benthic and the settlement of organic detritus onto the benthos. Unfortunately, there is no quantitative data describing the transfer rate between these populations.

II.4.2.2 The New England coast

Substrate types.--The coast is dominated by three morphological types: the rocky headland, the sandy beach, and the mud flat/marsh complex. Glacial till provided most of the sand that composes the beaches. The northern New England coasts are too rigorous to allow the deposition of much sand and they remain stripped of sediment. Most of the till was deposited at the edge of the glacier to the south, while the northern sections were stripped bare.

Generally, rocky coastlines are characterized by lack of sediment near the intertidal zone. Where beaches are present, the particle size of the sediments is large; most exposed eastern Maine beaches consist of pebbles up to small eroded boulders. Sand or mud flats exist only in embayments and estuaries far from the sometimes violent surf.

Sediment deposition determines the form of sandy beaches, unlike rocky shores. The processes by which sand beaches are formed is a mixture of physical and biological factors. McHarg (1970) provides a thorough description of all the processes involved in building and colonizing a sand dune beach. Obviously, the nature of the shoreline plays an important part of determining the nature of the coastal biota. In fact, very subtle changes in the size distribution of benthic sediment particles can cause major changes in the local benthic community.

One of the most important landforms of the New England coast is the estuary, a semi-enclosed coastal body of water which has free connection with the open sea and within which seawater is measurably diluted with fresh water derived from land drainage (Pritchard, 1935). Estuaries in New England have tended to be important centers for human activity since colonial times. The extremely diverse natural resources of estuaries make them ideal for settlement: estuarine river mouths provide safe harbors for trade, waterways inland, and rich food supplies of fish, shellfish, and waterfowl close at hand. Although much abused, estuaries serve as crucial links in the life cycles and food webs of coastal ecosystems.

Coastal communities.--Two marine communities are represented on the Gulf of Maine/Nantucket Sound/Long Island Sound coasts: barnacle-seaweed (Balanoid-Thallophyte), and shellfish-worm (Pelecypod-Annelid). The Balanoid-Thallophyte community is typical of the rocky coast benthos, while the Pelecypod-Annelid biome occupies unconsolidated sediments. In addition, there are tidal marshes which present some difficulty in categorization because they are marginal areas between different communities. They are zones of transition and are highly zonated in the same sense as rocky shores.

Shallow water benthic situaitons can be described as littoral and sublittoral. In sheltered places the littoral is essentially equivalent to the intertidal zone. On more exposed coasts, wave action and spray make any precise correlation with tide levels impractical, and the zones are best delineated biologically in terms of typical communities occupying different levels.

Subzones in the shelf benthos depend on differences in substratum. Water depth in this comparatively shallow section influences biotic distribution chiefly through its effects on light and temperature; water pressure is probably a relatively minor factor in comparison. The bathymetric range of individual species changes with latitude, and both northern and southern species tend to seek deeper, more stable levels when they intrude on the middle coast.

Estuaries and salt marshes.--Estuarine marshes are found along the entire coast. Marshes are transitional. Their initial formation requires a substratum bare for about half the tidal period; water calm enough to prevent the uprooting of the plants, and a sufficient supply of sediment to enable the upward growth of the marsh to keep pace with or exceed the rise in sea level due to glacier melt. Variation in substratum, drainage, aeration, and tidal cycling in addition to salinity produce a wealth of community subdivisions. The dominant species are usually botanical.

In quiet, submerged shallows the eel grass, *Zostera*, and another seed plant, *Ruppia*, dominate. Most of the invertebrates of the *Zostera* community actually are common on soft-ground habitats, but the population density is probably greater in the presence of eel grass. Among the swimmers and crawlers are several amphypods, the shore shrimp *Palaemontes* and *Crangon*, many snails and bivalves and a long list of worms.

Spartina alterniflora is the dominant grass in the mid-tidal area of the marsh. A typical assemblage at the lower *alterniflora* level illustrates the ecotonal qualities of the marsh as a transition between hard- and soft-ground biomes. The ribbed mussel *Modiolus* is a dominant form here providing a base of attachment for estuarine barnacles, bryozoans, anemones, and the fucoids *Ascophyllum* and *Fucus vesiculosus*. Throughout its range, which extends north through New England, the *Modiolus* assemblage includes a variety of small invertebrates.

S. alterniflora grows in the upper two-thirds of the littoral but is supplanted at elevations equal to or exceeding mean high water by high marsh communities. Plants growing at this level tolerate short-term daily submergence but require only a few wettings per month. This higher zone is dominated by short cord grass, *Spartina patens*.

Higher marsh associations harbor periwinkles and a characteristic snail, Melampus bidentatus, plus an assortment of salt marsh beetles, dipternas, and other essentially terrestrial arthropods. Fiddler crabs have extensive colonies at the same level on bare flats or in eroding banks adjacent to marsh areas. A terrestrial fauna with crickets, earwigs, oniscoid isopods, termites, and other small arthropods shelters under debris at the edge of the high marsh where there are patches of goldenrod and such xerophytic plants as Cakile, Salsola, and Atriplex. The "marine" contingent is represented here by salt marsh beach fleas, which are intolerant of prolonged or frequent submersion in water.

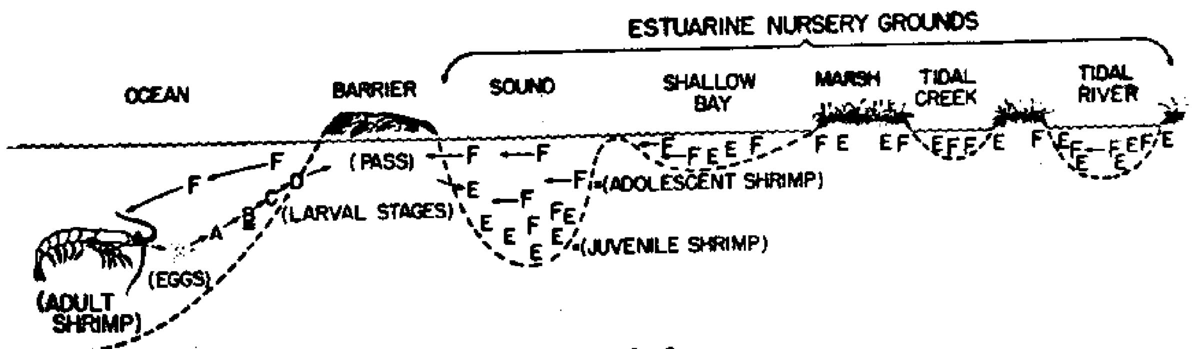


Figure II.4.6

Life history of shrimp that use estuaries as nursery grounds. Adult shrimp spawn offshore and the young larval stages (*A*, nauplius; *B*, protozoea; *C*, mysis; *D*, postmysis) move shoreward into the semienclosed estuaries where the juvenile (*E*) and adolescent (*F*) stages find the food and protection they need for rapid growth in the shallow bays, creeks, or marshes. The maturing shrimp then move back into the deeper waters of the sounds and adjacent ocean where they are harvested by commercial trawlers. (Odum, 1971)

Figure II.4.6 illustrates the role of the estuary/marsh complex as a nursery ground. The sequence of events for the shrimp is typical for many coastal invertebrates.

Intertidal relationships.--Like the estuary, another area where large gradients of environmental conditions exist occurs at the edge of the sea in the intertidal zone. Here are found organisms which can withstand the dessication that accompanies every low tide better than their competitors.

A conspicuous pattern of littoral zonation is one of the foremost characteristics of the community which occupies the intertidal zone along the coasts. Usually one or a few plants or animals dominate each community and give it a characteristic appearance. The broad scope of environmental variables produces a considerable diversity of different shores (Figure II.4.7).

Typically the sequence of biotic zones on a rocky coast (the Balanoid-thalophyte Biome to which we referred earlier) occurs as a series of horizontal color bands. The supralittoral zone is dominated by lichens and some periwinkle in the shaded, humid crevices. The barnacles define the top of the mid-littoral zone, sharing the substrate with the blue mussels. The lower mid-littoral zone is dominated by seaweeds, especially fucoids. Irish moss, *Chondrus crispus*, is also often found in the lowest range of the midlittoral area. The sublittoral area is covered by the laminarian seaweeds and other kelps.

The seaweeds of the rocky littoral shelter a rich invertebrate fauna that increases in abundance, both of individuals and of variety, at lower levels. The only conspicuous animals of the high barnacle-mussel level, aside from the dominants themselves, are dog whelks, and the limpets. The fucoids and other weeds provide both a hiding place and protection from dessication. Amphipods and worms occur in great profusion. Among the latter are turbellarian flatworms, nemertines, annelids, and nematodes. With these are encrusting bryozoans, hydroids, and small anemones.

Littoral members of the pelecypod-annelid community are, for the most part, burrowers. The perpetual instability of surf-beaten sand beaches imposes a Spartan regime, and the resident macrofauna is extremely limited. Most of the animals migrate with the tides. From the seaward side the

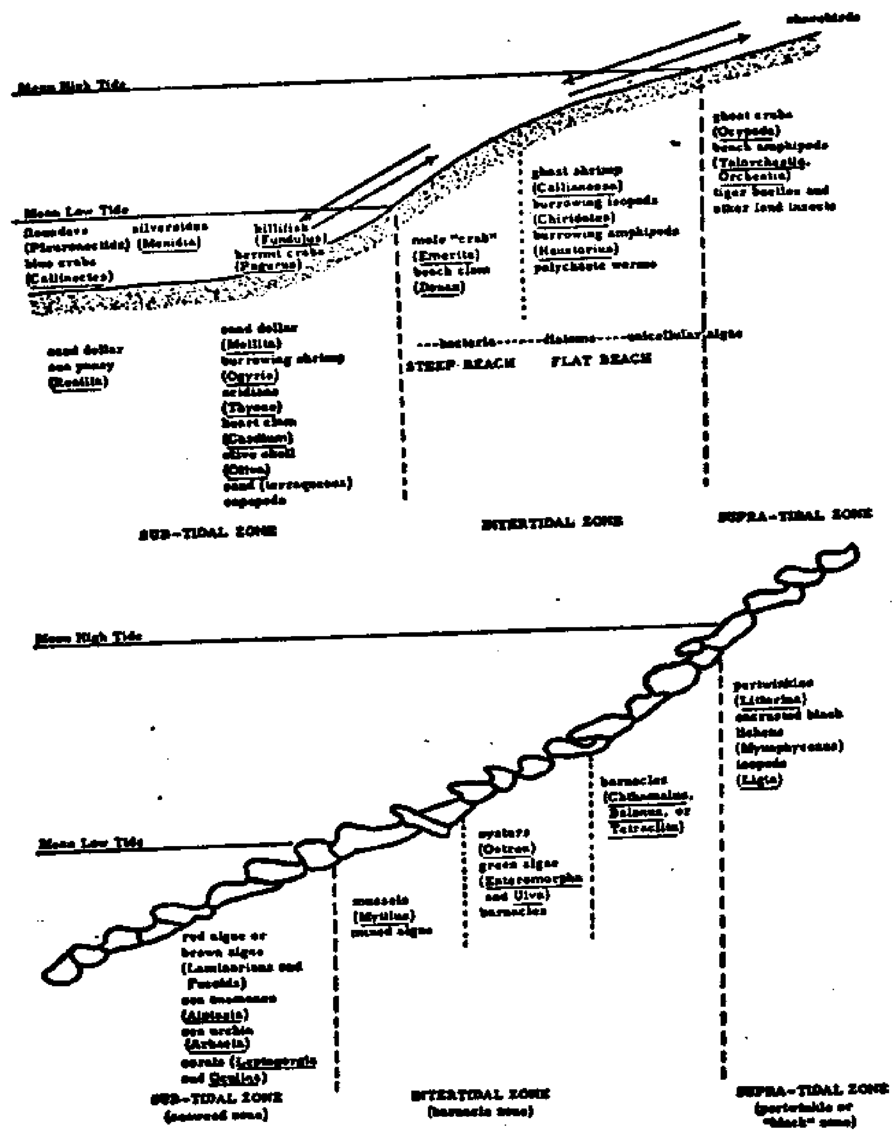


Figure II.4. 7

Transects of a sandy beach (upper) and rocky shore (lower). (from Odum,1971) hippid Emerita, and the south, wedge clams, Donax, move up and down the beaches in the swash zone of breaking waves, alternately burrowing and being disinterred. Amphipods of the family Haustoridae are especially characteristic of beach sand habitats. The microfauna of the interstitial waters of beach sand (psammo-littoral) has attracted increasing attention in recent years because of the abundance there of animals previously thought rare; they include various amphipods, gastrotrichs, tardigrades, and platyhelminthes; see Swedmark (1964) and references for the groups mentioned. From the land side, ghost crabs, Ocypode, and beach fleas, Talitridae, range down to the water's edge when foraging but have their burrows in the supralittoral. Almost sterile conditions may prevail on shingle beaches - shores covered with large pebbles and cobbles. These fragments are too coarse to permit burrowing, and the tumbling of such stuff by the surf constitutes a mill capable of grinding up the thickest armor. On beaches with mixed sediments a belt of shingle sometimes accumulates at the upper level reached only by storm waves. Beaches entirely of shingle occur commonly in the rocky coastal areas of Maine and northern Massachusetts, where subtidal deposits of glacial debris provide the raw material.

II.4.3 Composition and characteristics of crude petroleum and petroleum products

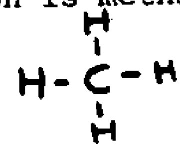
Crude petroleum is a complex mixture of hundreds of chemical compounds derived from biological matter which has accumulated in reservoirs in the earth and been subject to physical and chemical processes extending over millions of years. Petroleum from different geographical areas generally contains the same compounds but with different percentage composition. Because the biological effects of groups of similar compounds vary significantly, it is essential to consider the relative abundance of the various compounds in a particular crude oil or in a petroleum fraction which enters the environment. This section attempts to provide a brief introduction to the properties of these various compounds.

All petroleum compounds are composed of hydrogen and carbon; some also contain oxygen, nitrogen, sulfur, and a variety of other less common elements. A compound which contains only hydrogen and carbon is called a hydrocarbon. Compounds which contain other elements, in addition to hydrogen and carbon, are known as heterocyclic compounds. Figure II.4.7 indicates the relative proportion of hydrocarbon and non-hydrocarbon compounds in two typical crudes.

The properties of a compound (boiling point, solubility in water, etc.) depend on the different elements present, the number of atoms of each element in the molecule, and the structure that is formed when the atoms bond together. The empirical formula of a hydrocarbon compound, C_xH_y (where x is the number of carbon atoms and y is the number of hydrogen atoms), provides the number of atoms present, but says nothing about the structure they form. Actually, for any given C_xH_y, there are usually many possible structures, each having different properties. Thus, use of the empirical formula does not provide an unambiguous way of distinguishing between hydrocarbon molecules.

A carbon atom has the ability to form four bonds to other atoms (not necessarily carbon), while a hydrogen can bond to only one other atom:

The simplest hydrocarbon is methane:



which has the empirical formula CH_4.

Ethane, C_2H_6, is next in this series:

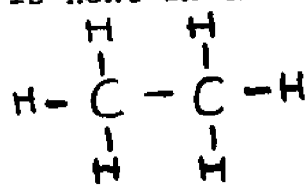
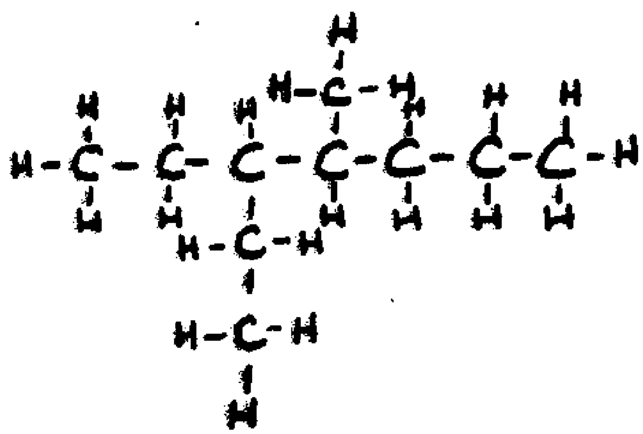


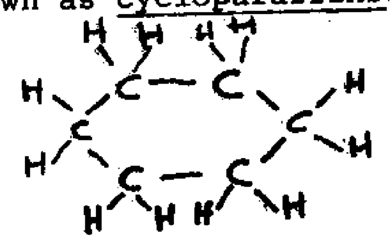
Table II.4.2 indicates the general characteristics of this series of hydrocarbons. Molecular weights increase by about 14 units as each CH_2 unit is added. Boiling points increase as molecular weight increases. Pentane is the smallest molecule which will remain a liquid at room temperature. The solubility data also reflects this. The value is normally given in grams of the hydrocarbon which will dissolve in a million grams of water at room temperature, but for methane, ethane, propane, and butane (which are gases at room temperature and pressure) the value is given in cubic cm. of the gas per 100 ml of water. In this series, all the empirical formulas fit the pattern C_nH_{2n+2}. Such straight chain hydrocarbons are called normal paraffins.

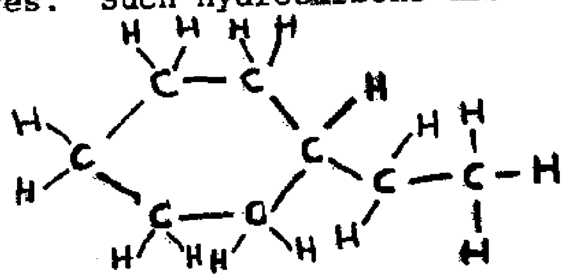
Compounds sometimes have side chains originating in the middle of the molecule such as that shown below. Compounds of this form are known as branched-chain paraffins. Note that these still conform to the C_nH_{2n+2} type of formula. Paraffins can make up to 25% of the composition of a crude petroleum. They tend to predominate in the low boiling

(40° - 230°C) portions of crude oil. They usually have a large number of different configurations due to different positions of the branch.



Alternatively, the carbon atoms may link together to form one or more ring structures. Such hydrocarbons are known as <u>cycloparaffins</u>:





Cycloparaffins may constitute from 30 to 60% of the composition of petroleum. Although the relative abundance of cycloparaffins does not change with boiling point, the type of compounds may differ from crude to crude. The principal change is the number of rings. Single ring compounds form a major part of the cycloparaffins although 2 to 6 rings are not unusual, and even 10 rings can be found in lubricating oils.

The number of hydrogen atoms associated with a given skeleton of carbon atoms may vary. When a chain or ring carries a full complement of hydrogen atoms, the hydrocarbon is said to be <u>saturated</u>. When less than the full complement of hydrogen atoms is present, the hydrocarbon is said to be <u>unsaturated</u>. Unsaturated hydrocarbons are characterized by having adjacent carbon atoms linked by two or three bonds instead of one. These double and triple bond links are much weaker than single bonds; as a result, the unsaturated hydrocarbons are more chemically reactive than saturates. In general, they are also much more water-soluble than the paraffins.

Straight or branched chain hydrocarbons containing double bonds are called olefins. Olefins are rather rare in crude petroleum. However, they are produced in sizable quantities during certain refining processes.

In crude petroleum, most unsaturated bonds appear in ring structures, in which case the compound is known as an aromatic. A typical crude might contain about 5% aromatics. In certain products, such as gasoline and light distillate, aromatics content can be as high as 20%. Aromatics, as we shall see, are biologically the most dangerous of the crude petroleum fractions. Most aromatics in petroleum are single ring. Polycyclic aromatic hydrocarbons are generally found in quantities representing a small fraction of 1%. These compounds are of interest since some members of this family are carcinogens.

Compounds containing both saturated and unsaturated rings are known as naphtheno-aromatics. Such compounds form a major component of higher boiling petroleum fractions.

The relative composition of the various fractions in terms of increasing molecular weight is illustrated in Figure II.4.8. The most dramatic change is the increase of naphtheno-aromatic compounds with increasing boiling point and the relative reduction of normal and branched chain paraffins. The range of hydrocarbon composition is shown in Figures II.4.9 and II.4.10. The distribution of hydrocarbons types by number of carbon atoms illustrates the wide variations that may occur.

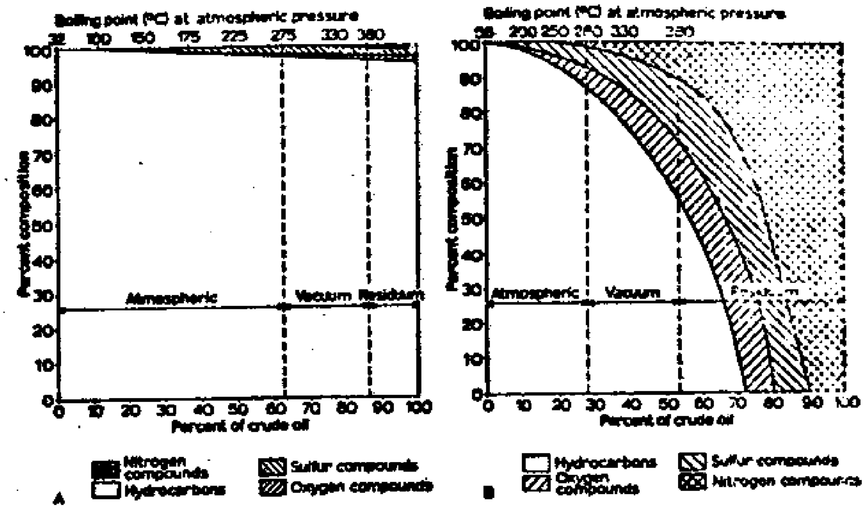


Figure II.4.7

Distribution of non-hydrocarbon components in two different crude oils. A = Ponca City crude oil; B = Wilmington crude oil. (Constantinides and Arich, 1967)

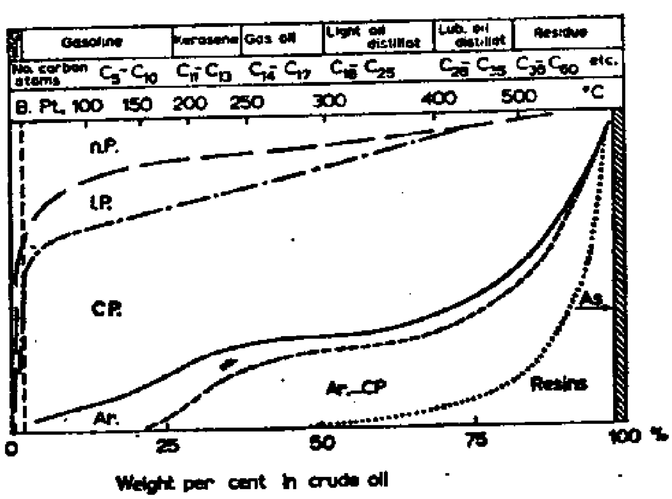


Figure II.4.8

Distribution of hydrocarbon classes in a medium crude oil. n.P. = normal paraffins; i.P. = iso-paraffins; CP. = cycloparaffins; Ar. = aromatics; Ar.-CP. = naphtheno-aromatics; Resins = heterocyclic compounds; As = asphaltenes. (Bestougeff, 1967)

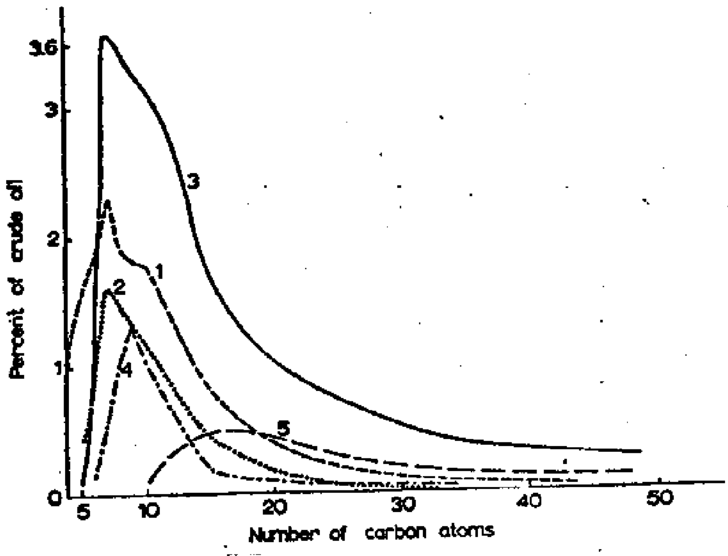


Figure II.4.9
Distribution of hydrocarbons in a light (Ordovician) crude oil. (By class and number of carbon atoms per molecule.) (Bestougeff, 1967)

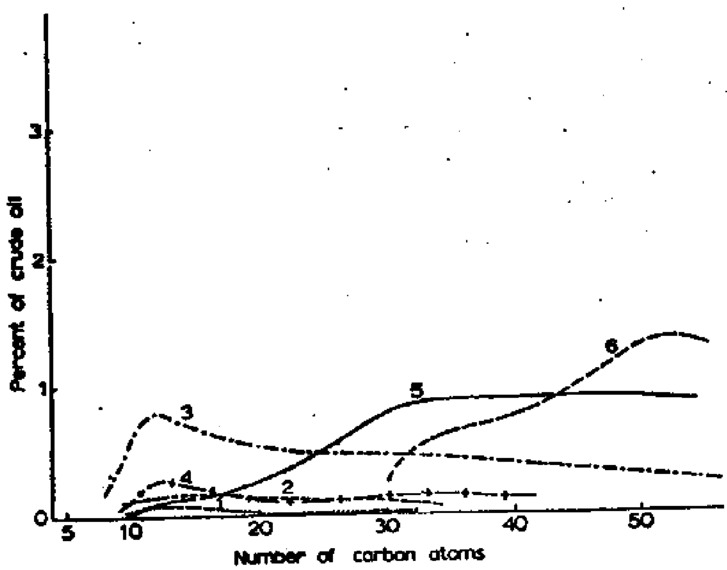


Figure II.4.10
Distribution of hydrocarbons in a heavy (Tertiary) crude oil. (By class and number of carbon atoms per molecule.) (Bestougeff, 1967)

Figure II.4.7 illustrates the relative abundance of non-hydrocarbon compounds in two typical crudes. Compounds containing sulphur in addition to hydrogen and carbon may represent from 5 to 40% of the curde. Sulphur is the most important non-hydrocarbon atom in petroleum and its compounds are found in increasing quantities in the high molecular weight portion of the crude (over 230°C). Oxygen compounds, acids, phenols, ketones, esters constitute up to 2% of crude petroleum. As with sulfur, oxygen compounds increase with boiling point, the greatest fraction found in the distillate over 400°C. Asphaltenes are heterocyclic compounds containing oxygen, sulfur, nitrogen and trace metals with molecular weights in the range of 900-3,000. They can represent a significant portion of the crude, from 0 to 20%. Though their composition is not completely known, they are essentially layers of condensed aromatic and naphthenic rings containing non-hydrocarbon atoms connected by short chains.

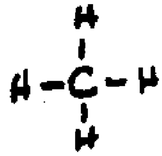
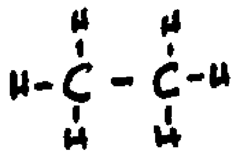
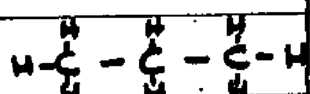
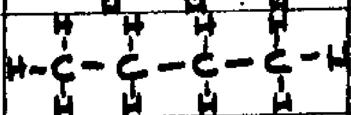
II.4.7.1 Classification by boiling point distribution

An alternative approach to characterizing petroleum is by boiling point distribution. Rather than consider chemical compound types specifically, broad boiling point fractions (distillation fractions) are used, each fraction containing a variety of chemical compounds. This approach has been used by the American Petroleum Institute and U.S. Bureau of Mines because the classification by boiling point relates directly to the crude's refinery characteristics. The relationship between the two methods of classification is illustrated in Figure II.4.8 and Table II.4.3.

The gas fraction (b.p. < 40°C) is of little interest for the purposes of this chapter. Gasoline boils between 40° to 180°C. It contains normal paraffins from C_6 to C_{12}, but also has substantial portions of branched paraffins, cycloparaffins and aromatics. Kerosene boils from 180° to 230°C. It contains normal paraffins C_{11} and

Table II.4.2

Structure and Properties of Alkanes

Empirical Formula	Structure	Molecular Wt.	Standard Name	Boiling Pt.	Solubility[a]
CH_4		16.04	Methane	-161.5	$9cm^3$ as a gas
C_2H_6		30.07	Ethane	-88.3	$4.7cm^3$ as a gas
C_3H_8		44.09	Propane	-42.2	$6.5cm^3$ as a gas
C_4H_{10}		58.12	Butane	-.5°C	$15cm^3$ as a gas
C_5H_{12}	etc.	72.15	Pentane	36.2	38.5
C_6H_{14}		86.1	Hexane	69	9.5
C_7H_{16}		100.2	Heptane	98.4	2.93
C_8H_{18}		114.23	Octane	125.8	.66
C_9H_{18}		128.25	Nonane	150.8	.22

a - in cm3/100ml for gases; in grams/10^6 grams otherwise

Table II.4.3 (Rossini, 1960)

Summary of the Amounts of the Broad Fractions Constituted by the Hydrocarbons Isolated from the Representative Petroleum

Broad fraction	Gas	Gasoline	Kerosine	Light gas oil	Heavy gas oil and light lubricating distillate	Lubricant fraction	Residue	Total
Boiling range at 1 atm. (°C)	<40°	40°–180°	180°–230°	230°–305°	305°–405°	405°–515°	...	...
Range of normal paraffins	C_1–C_5	C_6–C_{10}	C_{11} and C_{12}	C_{13}–C_{17}	C_{18}–C_{25}	C_{26}–C_{38}	...	...
Estimated percentage of the original petroleum constituted by the given fraction	4	33.2	12.7	18.6	14.5	10.0	7	100
Number of compounds isolated	7	101	37	12	10	8	...	175
Estimated percentage of the fraction accounted for by the hydrocarbons isolated	100	82.3	38.4	30.2	20.5	9.9	...	...
Estimated percentage of the original petroleum accounted for by the hydrocarbons isolated	4.0	27.3_3	4.8_1	5.6_1	2.9_7	0.9_9	...	45.7_1

Distribution, by Class and Broad Fraction, of the Hydrocarbons Isolated from the Representative Petroleum

Broad fraction	Gas	Gasoline	Kerosine	Light gas oil	Heavy gas oil and light lubricating distillate	Lubricant fraction	Total
Boiling range at 1 atm. (°C)	<40°	40°–180°	180°–230°	230°–305°	305°–405°	405°–515°	...
Range of normal paraffins	C_1–C_5	C_6–C_{10}	C_{11}–C_{12}	C_{13}–C_{17}	C_{18}–C_{25}	C_{26}–C_{38}	...
			Number of Compounds				
Classes of hydrocarbons							
Normal paraffins	5	5	2	5	8	8	33
Branched paraffins	2	35	...	...	...	...	37
Alkyl cyclopentanes	...	22	...	...	...	...	22
Alkyl cyclohexanes	...	13	1	...	...	...	14
Alkyl cycloheptanes	...	1	...	...	...	...	1
Bicycloparaffins	...	4	6	...	...	...	10
Tricycloparaffins	...	...	1	...	...	...	1
Alkyl benzenes	...	20	20	...	...	...	40
Aromatic cycloparaffins	...	1	6	1	...	...	8
Dinuclear aromatics	...	...	1	6	1	...	8
Trinuclear aromatics	...	...	...	...	1	...	1
Total	7	101	37	12	10	8	175

C_{12}, and a substantial proportion of aromatics, naphtheno-aromatics, and cycloparaffins. Light gas oil boils between 230° and 305°C and contains normal paraffins from C_{13} to C_{17}. Aromatics, naphthenes and naphtheno-aromatics are major components. Heavy gas oil and light lubricating distillate boils between 305° to 405°C and contains normal paraffins from C_{18} to C_{25}. A number of tri- and tetra-cyclo aromatic compounds are present as well as naphtheno-aromatics. Increasing percentage of sulphur, oxygen and nitrogen compounds are present. Both diesel fuel and distillate fuel oil are blended mixtures of these boiling point fractions and have similar boiling range, 170° to 370°C respectively. They include kerosene, light gas oil, heavy gas oil, and light lubricating distillate fractions discussed above. Lubricant fraction boils from 405° to 515°C and contains very small amounts of C_{26} - C_{38} normal paraffins. It is essentially multiple ring naphtheno-aromatics. Compounds with boiling points in excess of 515°C are known as residual fuel.

II.4.7.2 Oil weathering

Oil is a complex mixture of many chemical compounds and the characteristics of spilled oil are altered significantly by evaporation, dissolution, microbial and chemical oxidation (Dean, 1968; Blumer and Sass, 1972). Blumer and Sass (1972) and Blumer et al. (1972) have recently reported data on these various degradation processes. Because the varying constituents of oil are affected at different rates by these "weathering" forces the relative composition (and therefore biological effects) of the spilled oil will vary markedly with time since spill.

The large number of individual compounds in crude oil precludes the consideration of the weathering of each one separately. Throughout the sequel, therefore, we will characterize the oil according to the eight fractions shown in Table II.4.4 which indicates estimates of the range of physical/chemical constants for each fraction. The eight fractions selected provide flexibility in characterizing oil, especially with respect to biological effects, both short- and long-term, without confusing the problem with excessive data. More detailed breakdowns are possible and could be warranted in some cases. The role of each weathering component is briefly described below (Blumer, 1970).

Evaporation into the atmosphere depletes the lower boiling components (fractions 1, 3 and 5, Table II.4.4) but leads to little or no fractionation between hydrocarbons of the same boiling point that belong to different structural series.

Dissolution into seawater also removes preferentially the lower molecular weight components of an oil. However, aromatic hydrocarbons have a much higher solubility than paraffins of the same boiling point. The amount of oil dissolved into surrounding seawater is critical to many of the biological effects associated with spills. Notice that the solubility of the various fractions varies over an extremely large range.

Biochemical (microbial) attack affects compounds within a much wider boiling range than evaporation and dissolution. Hydrocarbons within the same fractions are attacked roughly at the same rates. Normal paraffins are most readily degraded. In gas chromatograms this type of degradation manifests itself as a lowering of the ratios between straight chain and adjacent branched paraffins. Extended biochemical degradation then results in gradual removal of the branched paraffins. Cycloparaffins and aromatic hydrocarbons (fractions 3-8) are more resistant and disappear at a much slower rate.

Chemical degradation processes of oil during weathering are not well understood. However, the overall result

Table II.4.4
BASIC DATA FOR OIL
SPILL WEATHERING MODEL

Fraction	Description[a]	% by wt.[a] in Crude Oil	Density[b] (gm/ml)	Boiling Point[b] (°C)	Molecular Weight[b]	Vapor Press.[b] @ 20°C (mm)	Solubility[c] ($gm/10^6 gm$ Distilled H_2O)
1	Paraffin C_6-C_{12}	.1-20	.66-.77	69-230	86-170	110-.1	9.5-.01
2	Paraffin C_{13}-C_{25}	0^+-10	.77-.78	230-405	184-352	.1	.01-.004
3	Cycloparaffin C_6-C_{12}	5-30	.75-.9	70-230	84-164	100-1.	55-1.
4	Cycloparaffin C_{13}-C_{23}	5-30	.9-1.	230-405	156-318	1.-0	1.-0
5	Aromatic (Mono- and di-Cyclic) C_6-C_{11}	0-5	.88-1.1	80-240	78-143	72-.1	1780.-0.
6	Aromatic (Poly-Cyclic) C_{12}-C_{18}	0^+-5	1.1-1.2	240-400	128-234	.1-0	12.5-0
7	Naphtheno-Aromatic C_9-C_{25}	5-30	.97-1.2	180-400	116-300	1.-0	1.-0
8	Residual (including non-hydrocarbons)	10-70	1.-1.1	>400	300-900	0	0

(footnotes on following page)

Table II.4.4 (continued)

a - taken from:

1. Bestougeff, M.A. in Nagy, Bartholomew and Colombo, Fundamental Aspects of Petroleum Geochemistry, Elsevier Publishing Company, New York, New York, 1967.

2. Rossini, Fredrick D., Hydrocarbons in Petroleum, Journal of Chemical Education, Vol. 37, No. 11, November 1960.

3. Smith, H.M. Qualitatitive and Quantitative Aspects of Crude Oil Composition, U.S. Bureau of Mines Bulletin 642, 1968.

b - taken or estimated from:

1. Handbook of Physics and Chemistry

2. Physical/Chemical Constants for Organic Compounds

c - taken or estimated from:

1. Klevens, H.B., Solubilization of Polycyclic Hydrocarbons, Journal of Petroleum Chem., 54:283-298 (1950)

2. Peake, Eric, and G.W. Hodgson, Alkanes in Aqueous Systems. II. The Accommodation of C12-C13 n-Alkanes in Distilled Water, J. Am. Oil Chemists' Society, Vol. 44, pp. 696-702, Dec. 1967.

3. McAuliffe, Clayton, Determination of Dissolved Hydrocarbons in Subsurface Brines, Chem. Geol., 4(1969), 225-233.

4. Gerarde, H.W., Toxicology & Biochemistry of Aromatic Hydrocarbons, Elsevier Publishing, London, 1960.

appears analogous to that obtained in technical oxidation processes (e.g. "blowing" of asphalt). Oxidation affects most readily the aromatic hydrocarbons of intermediate and higher molecular weight.

The effect of these weathering processes is the rapid depletion of lower boiling fractions (boiling point < 250°C) from a crude oil slick by evaporation and dissolution and slow degradation of higher boiling fractions by microbial and chemical oxidation. Figures II.4.11, II.4.12, and II.4.13 illustrate the rate at which these weathering processes occur. Figure II.4.11 is a plot of field experiment data on oil weathering from Kinney et al. (1969) and Smith and MacIntyre (1971). The short-term loss from spilled oil of compounds such as undecane (C_{11}), illustrated in Figure II.4.11, results almost exclusively from evaporation and dissolution, because microbial and chemical oxidation are only important in oil weathering over much longer time periods. The total rate of loss by evaporation and dissolution can be estimated from the slope of the curves in Figure II.4.11. However, the rate is highly dependent on wind speed, as shown by the data of Smith and MacIntyre. The slope of the curve in Figure II.4.11 increases sharply as the wind increases from <1 to 18 knots. The slopes of the curves in Figure II.4.11, which are a measure of the loss rate, are plotted versus wind speed in Figure II.4.12. Because the data from Kinney et al., which was taken under conditions of constant wind, is nearly a straight line on a semi-log plot, the weathering process is assumed to be a first-order decay. The decimal fraction remaining of a particular oil component at any time after a spill is then equal to e^{-rt}, where r is the weathering rate (per hour) and t is the time interval (hours) since the spill. The weathering rate, r, is equal to 2.3 (conversion from $\log_{10}$ to $\log_e$) times the slope of the line obtained from a plot such as in Figure II.4.11. In the particular case at hand, in which the slopes in Figure II.4.11 are an exponential function of wind speed, r is estimated from Figure II.4.11 to be equal to $.11e^{.2s}$, where s is the wind speed in knots. As a first such crude or petroleum product can be characterized by percentage composition of the eight fractions. Using the solubility data it is then possible to estimate the amount of the various fractions that could actually go into solution in any given situation. Table II.4.5 summarizes estimates of these data. The maximum proportional soluble ranges from 1% or less for residual up to 60% for light distillates.

approximation this rate of weathering by evaporation and dissolution can be assumed valid for fractions 1, 3, and 5 of Table II.4.5, which have solubilities and volatilities similar to undecane. More importantly, this estimate of rate of short-term weathering may be used to predict the length of time for any specified percent of the low boiling, high solubility oil components to be lost from an oil slick, given a particular wind speed. For example, if there is no wind, the approximate percent of fractions 1, 3, and 5 remaining in a slick after 24 hours is equal to $100e^{(.11)(24)}$ or about 10% and in 96 hours there would be only a very small fraction of a percent remaining in the slick. In a strong wind, virtually all of these fractions are likely to be lost in 24 hours.

Evaporation and dissolution are not readily separable from this data. However, most of the increase in total loss rate by the wind can be attributed to the wind effects on evaporation. Therefore, dissolution is certainly less than the minimum total loss rate. Furthermore, the large difference between gas and liquid diffusivity rates (gas diffusivities are typically one or two orders of magnitude greater than liquid diffusivities) indicate that dissolution is considerably less than the minimum total loss rate. Based on these considerations, it is estimated that evaporation accounts for one to ten times as much of the loss of fractions 1, 3, and 5 as does dissolution. Note that due to the higher solubilities (see Table II.4.5) of aromatic compounds relative to paraffins (for the same boiling point range), it can be expected that evaporation may account for less of the total loss of aromatics than for paraffins.

Figure II.4.13 illustrates the microbial degradation of higher boiling fractions using data on $n\text{-}C_{17}$ (heptadecane). Because pristane is not degraded until after $n\text{-}C_{17}$ is oxidized, the ratio of these two is a measure of microbial oxidation. Fractions boiling higher than $n\text{-}C_{17}$ have degradation rates orders of magnitude slower than that obtained for $n\text{-}C_{17}$ ($\sim$ .01/day).

*This page replaces page 198 Volume II, MITSG 73-5

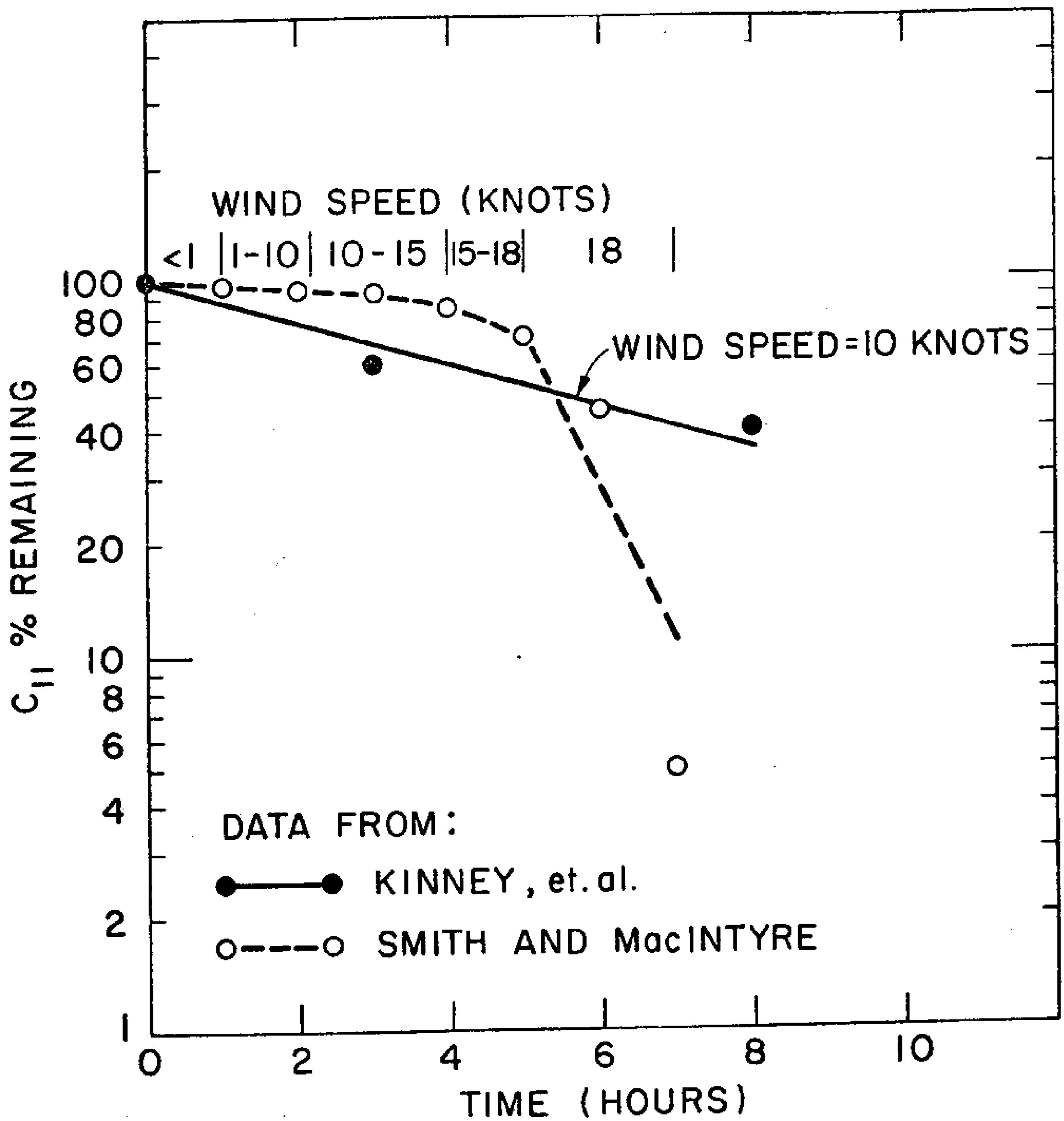


FIGURE II.4.11

LOSS OF UNDECANE (C_{11}) BY EVAPORATION AND DISSOLUTION

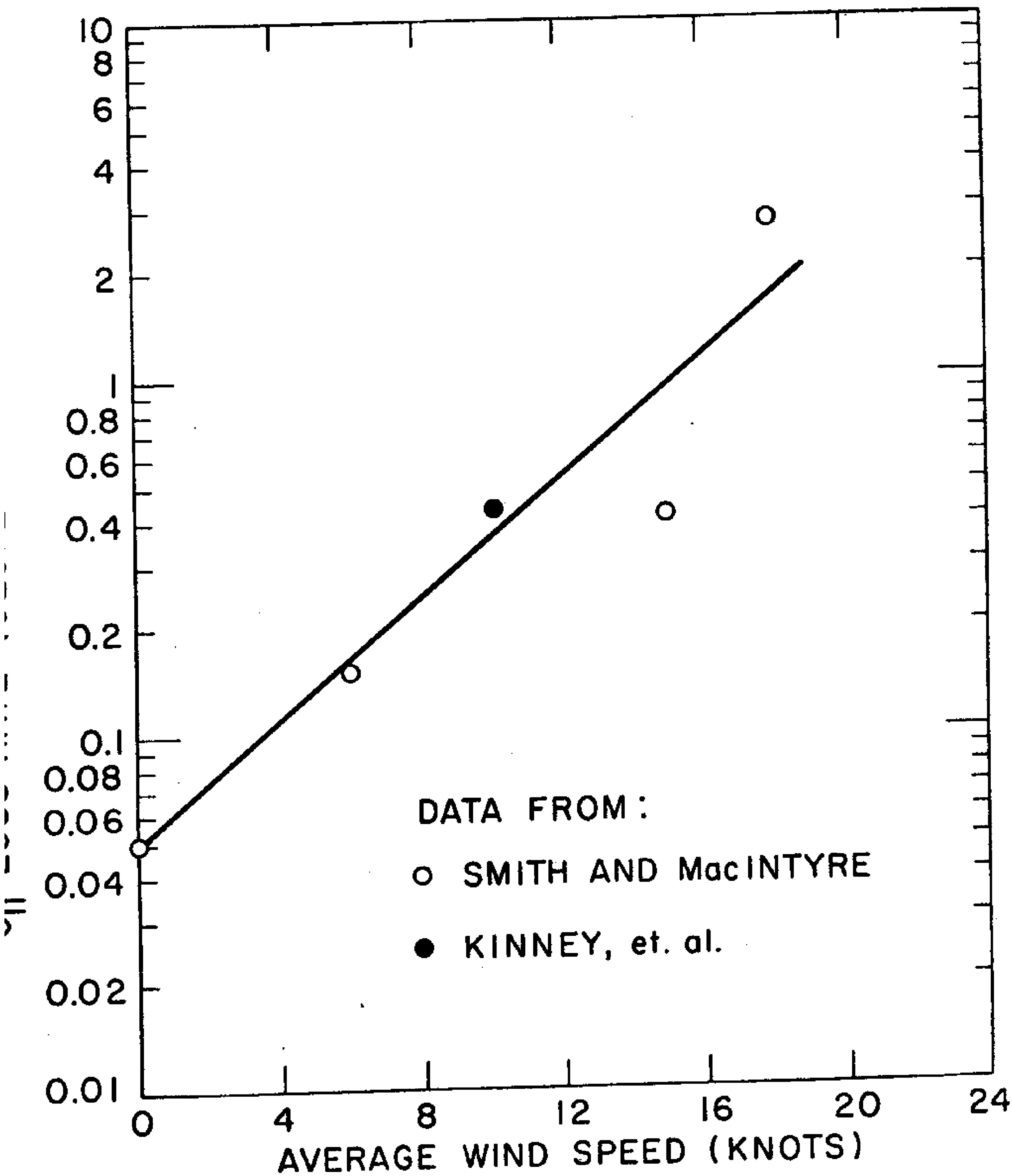


FIGURE II.4.12

EFFECT OF WIND SPEED ON WEATHERING

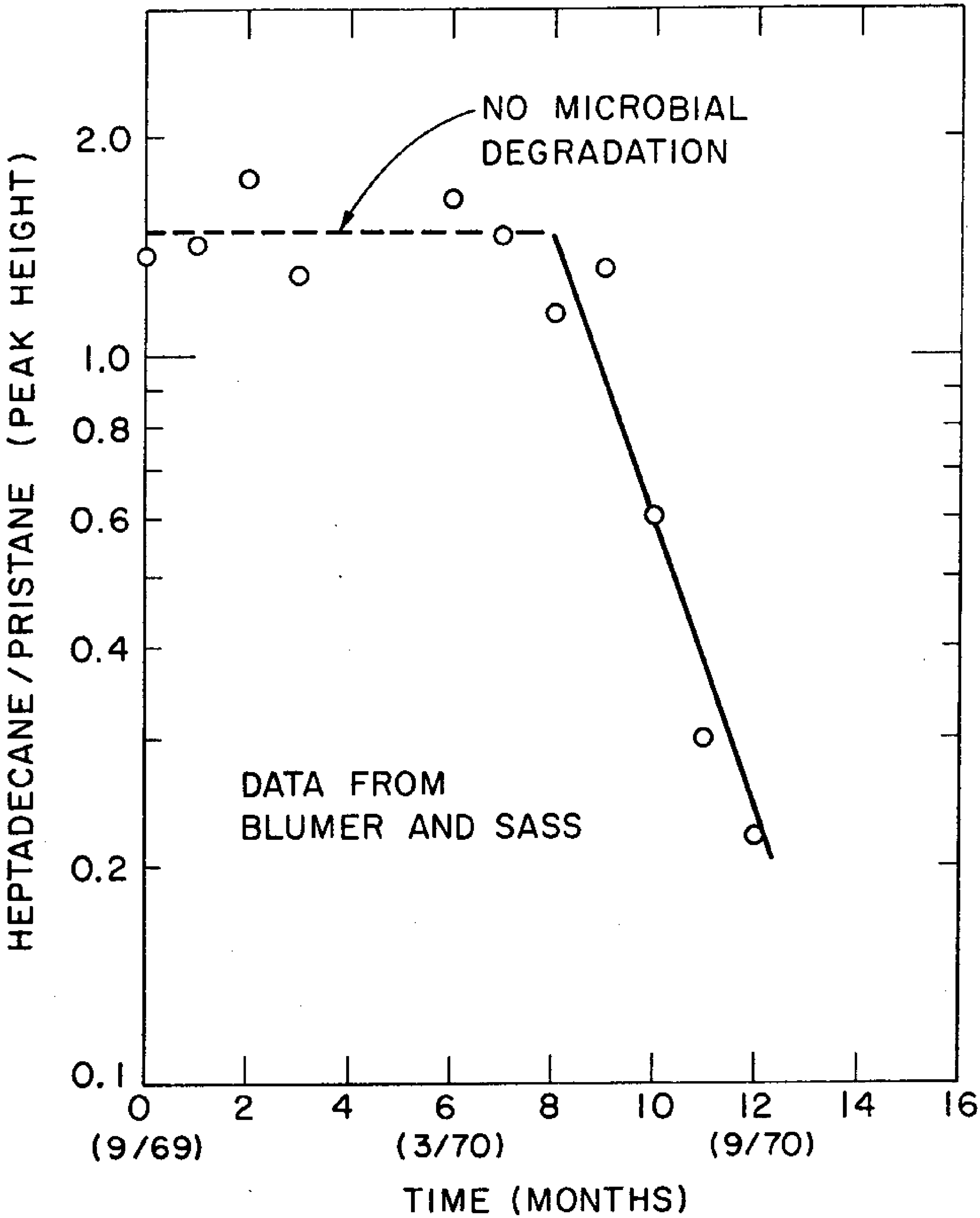


FIGURE II.4.13

MICROBIAL DEGRADATION OF HYDROCARBONS

Table II.4.5

Estimated % Composition (by weight) and Comparison of Solubilities For Various Petroleum Substances

FRACTION	DESCRIPTION	(HEAVY) CRUDE A	(MEDIUM) CRUDE B	#2 FUEL OIL	KEROSENE[c]	RESID.
1	Low Boiling Paraffins	1	10	15	15	0
2	High Boiling Paraffins	1	7	20	20	1
3	Low Boiling Cyclo-Paraffins	5	15	15	20	0
4	High Boiling Cyclo-Paraffins	5	20	15	20	1
5	Mono- and Di-Cyclic Aromatics	2	5	15	15	0
6	Polycyclic Aromatics	6	3	5	2	1
7	Naphtheno-aromatics	15	15	15	8	1
8	Residual	65	25	—	—	96
Estimated Maximum % Soluble		10	30	60	65	1
Estimated Maximum % Soluble Aromatic Derivatives		.1-10	.1-10	1-30	1-20	0-1
Reported % Soluble Aromatics Obtained In Seawater Extracts		.1[b]	.01[a], .1[b]		.01[a]	

a. Boylan and Tripp (1971); Kuwait and kerosene extracts

b. Kuhnhold (1970); medium crude extract

c. Table values for BP 1002 would be similar to kerosene

II.4.4 Effects of oil on marine organisms

Introduction.--An examination of the effects of oil on biological systems must begin with a discussion of the influences of oil on individual organisms. Determination of effects on higher levels of the biological hierarchy (populations, communities, and ecosystems) are then possible, but more difficult. Section II.4.4.1 establishes terminology and a general outline of oil effects on individuals and the transmission of the harmful effects of oil through higher biological levels. Detailed assessments of the sensitivities to oil, and identification of critical concentrations for various marine organisms are included in Section II.4.4.2.

II.4.4.1 A framework

Individuals.--An individual organism is a complex structure consisting of many interconnected components: cells join together to form organs, which perform specialized functions; organs form less specialized systems; systems act together to maintain the whole organism. The first level at which a clear division is possible is the individual cell. The cell membrane serves as a highly selective barrier, allowing necessary substances into the cell, blocking out unwanted substances. It is an active process; the membrane uses energy to select between substances. Within the cell, specialized structures called organelles carry out the metabolic biochemical processes of the cell (e.g. respiration, photosynthesis, cell division). Enzymes play an essential role speeding up biochemical reactions and allowing the cell to function. The direct contact of a harmful substance (e.g. a virus particle or oil) with an individual cell either kills the cell or is not harmful and the cell continues with its normal operations. Thus, at the level of each individual cell, the effects of a pollutant tend to be an "all or none" response.

Hydrocarbons may disrupt the cell in several ways including alteration of the cell membrane and the inhibiting of enzymes and other metabolically important molecules within the cell. Hydrocarbons are known to disrupt the lipid (fatty molecule) layer of the cell membrane, increasing its permeability (the ability for molecules to pass back and forth through the membrane) and causing death through the loss of vital cell components. Some organisms are able to resist the effect of crude oil because of their ability to metabolize (break down and oxidize) the hydrocarbons which enter the cells, and, in some cases, the ability of their cell membranes to resist the intrusion of hydrocarbons altogether.

In general, the low boiling aromatic and aromatic derivative components of crude oil have proven to be the most toxic. However, low boiling straight chain paraffins (10-12 carbons) may also cause a narcotic effect.

If cells are disrupted by oil, there is the possibility that the organs or organ systems which are composed of cells may also be disrupted. For the purposes of this study, any disruption at or below cellular level is defined as a <u>cellular effect</u>, while any disruption above the cellular level dealing with involuntary (biochemical) processes is defined as a <u>physiological effect</u>. Examples of physiological processes are blood circulation, secretion of digestive juices, and blood purification by filtration through the kidneys. Processes that are under instinctive and/or voluntary control are defined as behavioral. Examples are feeding and reproduction.

This categorization of oil effects is not always satisfactory. The death of cells may or may not disrupt organ functions which in turn may or may not alter the operation of the organ system, and so on. Each of these possibilities depends on many factors, such as the composition and amount of oil, the sensitivities of the cell, organ and physiological system, the sensitivities of the cells in other physiological systems, and interactions among systems affected by the oil. Furthermore, cellular, physiological and behavioral effects are strongly linked. For example, if impulse transmission between cells in the nervous system is affected by oil, the behavior of the organism may be upset. Thus, the entry of oil into cells kills the organism or disrupts its behavior. A series of cascading effects in the individual organism leading from cellular through physiological to behavioral disruption undoubtedly exists for each organism that is sensitive to oil, the magnitude of the disruption being related to the particular organism's sensitivity to the oil.

In order to better describe the specific effects of oil on an individual organism five responses can be identified: (1) lethal toxicity; (2) sub-lethal disruption of physiological or behavioral activities; (3) the effects of direct coating by oil; (4) incorporation of hydrocarbons in organisms which cause tainting and/or accumulation of hydrocarbons in food chains; and (5) changes in biological habitats.

Lethal toxicity refers to the direct interference by hydrocarbons with cellular and sub-cellular processes, especially membrane activities, leading to organism death. Sub-lethal disruption also refers to interference with cellular and physiological processes but does not include effects causing immediate death. The most important effects in this category are disruption of behavior, especially feeding and reproduction. The effects of direct coating do not result from biochemical interference of oil with cellular activities. The primary effects are smothering or mechanical interference with activities such as movement and feeding. The incorporation of hydrocarbons in organisms is of interest for two reasons: (1) because of potential accumulation of polycyclic aromatic hydrocarbons (PAH), especially carcinogens, in various marine organisms

(2) tainting of edible organisms with hydrocarbons. Habitat changes include effects from both oil spill and non-oil spill events. This group of effects consists of changes in the physical or chemical environment, which result in significant shifts in species composition and geographic distribution in the region of concern.

The relationship between cellular, physiological, and behavioral effects and toxicity, sublethal effects, coating, hydrocarbon incorporation and habitat changes are summarized in Table II.4.6. Effects which alter behavioral patterns do not usually cause death directly, although an organism may be more susceptible to predation due to abnormal behavior. At the cellular level, hydrocarbons are usually either toxic to individual cells or have no direct effect at all. Weathered oil consists of high molecular weight hydrocarbons and is not transported into the cell, but may suffocate the organism by cutting off its source of oxygen. Habitat changes are usually caused by weathered oil which changes sediment textural characteristics.

Higher levels of organization.--The impact of oil at each succesive level of biological organization (individual population, community and ecosystem) is dependent on the impact at the previous level plus other variables unique to each level. Unfortunately the basic principles governing organization at each level are not that well understood and the ultimate assessments of impacts on an ecosystem are very difficult to quantify.

At the population level, a key variable is reproduction strategy. Conventionally, we speak of "r strategies" and "K strategies". That is, populations may adopt reproduction strategies which depend upon increasing r, the population rate of increase, or increasing K, the maximum supportable population in the environment. Most marine invertebrates are r strategists, producing many more offspring (high potential r) than can possibly be supported

Table II.4.6

Important Possible Effects of Oil
On Individual Organisms

Location of Action / Effect	Cellular	Physiological	Behavioral
Lethal Toxicity	✓	✓	
Sublethal Effects		✓	✓
Coating With Weathered Oil		✓	✓
Incorporation of H.C.'s Into Food Webs	✓	✓	
Changes In Habitat		✓	✓

in the environment. On the other hand, birds and mammals are typically K strategists, i.e. maximum r is low, but chances of survival to adulthood are reasonably high. For an r strategist a few surviving adults can produce enough young to maintain and increase a population. However, a K strategist is dependent upon maintaining a relatively large reproducing population. In general, the long-run impact of a given kill on an r strategist and on a K strategist can be quite different.

Beyond the population level, any inference about the effects of oil on interactions between populations (i.e., a community) becomes difficult. Species interactions within the Georges Bank community form an exceedingly complex dynamic system, the interrelations of which vary markedly with season and the age of the individuals in the species. For example, pollock, herring, and mackerel eat their own and each other's eggs and larvae, as well as copepods. The fish larvae eat phytoplankton as well as each other. Species which are predators on another species at one point in the life cycle can reverse positions at another point. In general, most species' feeding habits are remarkably catholic. Underlying this are continual variations in basic nutrients, temperature, salinity, and current patterns. Finally, the various species vary in their sensitivity to oil. For example, if one member of the phytoplankton was seriously reduced by oil, it is impossible at this point to predict to what extent this loss in food for higher level species would be made up by in migration or blooms of other species.

At one point, the study group envisioned development of a quantitative model for simulating the population dynamics of Georges Bank and shoreline communities. However, the necessary data base and knowledge to make this a useful enterprise simply does not exist at this time. Thus, our biological inferences will necessarily be limited to species-level statements in this report.

II.4.4.2 The data

Before discussing the documented responses of organisms to oil, it is necessary to review the experimental procedures which provide the data base. Although a substantial number of studies have been carried out, investigating various biological aspects of oil pollution, there have been no comprehensive systematic studies of the whole problem as yet. In addition, there is a lack of standardization of the results of various studies. Accurate measurements have not been made of the concentration and composition of crude petroleum in solution, and the concentration and composition of fractions of petroleum in the bodies of animals and plants tested. Thus, in most cases, important pieces of information that provide the basis for comparison of different studies are missing. The complexity of petroleum amplifies this problem and makes it difficult to accurately analyze and specifically attribute biologically observed effects to even a limited fraction of the crude petroleum. Finally, a number of physical and biological processes significantly change the composition of crude petroleum over time, adding further difficulties. Despite these problems, there is enough information available to intelligently discuss various effects, the specific sensitivities of representative biological organisms, and draw some conclusions about the overall effects of crude petroleum and petroleum products.

Laboratory experiments are designed to examine the biological consequences of the controlled exposure of plants and animals to specific concentrations of pollutants. These experiments normally consist of a number of animals or plants of a particular species (e.g. fish, shellfish, algae) being placed in a large tank in which they are exposed to water or sea water containing petroleum components. The organisms are allowed to remain in the tank for varying periods of time (from minutes to hours), and then removed and, if still alive, may be placed in non-polluted water for varying periods.

Most studies evaluate the so-called acute toxicity, which is reported as the dose required to kill a specified percentage (usually 50%) of the test organisms during the exposure period. Various notations are used. This report uses χLD_y, where χ denotes the exposure period in hours and y denotes the percentage killed. For example, $8LD_{50}$ would be the dose required to kill 50% of the test organisms in 8 hours. In a few experiments, the organisms that survive the acute effects are observed for longer periods of time (days to weeks) and long-term toxicity and sub-lethal effects evaluated. Todd, et al. (1972) and Whittle and Blumer (1970) have reported the only extensive experiments which deal explicitly with the influence of sub-lethal concentration on behavior, survival, reproduction and community structure.

There are several severe limitations to the usefulness of experiments such as those described above. Most importantly, no standard experimental methods have been developed, especially with respect to petroleum fractions and media monitoring. The variability of composition, limited solubility and weathering of petroleum products require that the soluble fractions in the media be measured during the toxicity tests. However, this is almost never done. As a result, comparison of data is extremely difficult because different petroleum substances and different methods of addition (surface film, emulsion, etc.) are utilized in different experiments. Furthermore, the organisms are subjected to unnatural conditions and deprived of important interactions with other species and other normal environmental conditions.

Concentrations of hydrocarbons in the tissues of test organisms, before and after the exposure to oil, are rarely determined. The gas chromatography and spectroscopy equipment used in analyzing hydrocarbons is expensive and relatively complex, thus inhibiting widespread application to oil toxicity studies. Because these analytical techniques have not been extensively used as yet, little data is available relating to background concentrations of hydrocarbons in the environment and in the tissues of individual species.

Even if hydrocarbon concentrations in animal tissues are measured after exposure, they are often reported in a form which makes comparisons with other studies difficult. Hydrocarbon concentrations are reported in the literature as grams per kilogram of dry weight tissue, or grams per kilogram of wet weight tissue, thus leaving to the reader the task of determining what percentage of the test organism is water. Frequently, the petroleum additive is described in the literature merely as "oil", "light crude oil", "mineral oil", etc., omitting important information about composition, especially soluble fractions. Due to these shortcomings, the primary value of laboratory experiments is to establish order of magnitude boundary conditions on lethal toxicity. That is, concentrations of various substances can be identified which, if significantly exceeded, have a high probability of killing the organism of interest.

Only a limited number of experiments on plants and animals in the field have been undertaken. They consist of spraying or pouring crude oil, weathered crude oil, or petroleum products on specific areas in salt marshes or various coastal areas. Changes in fauna or flora are noted for various periods after their exposures. Spraying may be repeated at different time intervals over a period of months or years. The results are normally described as quantitative changes of numbers and density (number of organisms per unit area) of animals or plants present. In general, field experiments have the advantage of taking place in a "natural" habitat, thus allowing complex effects related to survival in an ecosystem to be evaluated. However, they are less quantitative and controlled. Frequently, the concentration of oil applied per unit area is not known precisely. In addition, although the experiments take place in a natural setting, they may be so restricted in size that significant effects are not observed. A number of variables, such as predators, weather conditions, and physio-chemical changes, cannot be controlled, and frequently are not noted in the literature. Major salinity changes because of runoff from heavy rains occurred in the Santa Barbara Channel at the same time as the oil spill. It is difficult to distinguish between deathsattributed to "natural" changes and those due to oil.

Extensive data is available from studies following actual accidental spills. Unfortunately, prior examinations of the flora and fauna affected is usually not available. Typically, these studies describe the organisms remaining and their recovery, but do not include estimates of the concentration of hydrocarbons to which the organisms were exposed. Often, dead organisms are counted, although only rarely are hydrocarbon concentrations in their tissues measured. The actual impact of a spill is highly dependent on weather conditions, time of year, local hydrography and physiography, and the area's previous history of oil spills. The length of time between release of the oil and its coming ashore are rarely directly stated in the literature. However, the extent of weathering that the slick has undergone can usually be ascertained by closely examining the description of the accident causing the spill, which usually precedes discussion of biological effects in the article.

Assessments of the various effects of oil on individual organisms is summarized in the paragraphs below. For each of the five classifications of effects data reported in the literature is summarized for several organism categories including: flora (phytoplankton, kelp, marsh grasses, etc.), pelagic fauna (finfish, crustaceans, larvae, etc.) and benthic fauna (molluscs, crustaceans, etc.).

Lethal toxicity.--The data summaries for toxic responses (Tables II.4.7 through II.4.14) follow a standard format. For each organism or group of similar organisms the tables specify the common and scientific names, the type of experiment (laboratory, field or actual spill incident), the substance and amount used or spilled, an estimate of the actual amount of aromatic derivatives in solution, the test duration, the reported response, a reference citation and general remarks. Because toxic responses result almost exclusively from the soluble fractions of oil, it is important to determine the concentration of soluble hydrocarbons. In almost all reported cases this information is not provided. The estimates shown of soluble aromatic derivatives were made by reference to Table II.4.5, which compares a variety of petroleum substances, and from the description of experimental methods given by the original authors. Soluble paraffin fractions are not included, because only the very low boiling fractions (less than C_{10}) are toxic and even these only in nearly saturated solutions (Goldacre, 1968; Nelson-Smith, 1970) which would not be obtained under test or field conditions with petroleum mixtures.

Table II.4.7 summarizes the toxic response of marine flora to hydrocarbons. Phytoplankton sensitivities vary over a wide range. A few species are apparently sensitive to concentrations of soluble aromatic derivatives (SAD) as low as 1 ppm. However, most species are unharmed by concentrations of 100 ppm or higher. Kelp are affected similarly. Note that Wilbur (1968) reports no effects on kelp by the paraffin hexane (10 ppm), but significant effects of the aromatics benzene and toluene (10 ppm). Kelp and other macrophytes can be expected to be reasonably resistant due to excretion of mucous substances, which coat the stems and fronds of the plant, preventing damage. Most data for the response of marsh grasses deals with effects of coating. However, it is reasonable to assume a toxic response to SAD concentrations of 10-100 ppm. Baker (in Cowell, 1971) provides a summary of the effects of oils on plant physiology. The long-term effects of spilled oils on plants depends on both toxic and coating effects, frequency of coating, and on the time of year.

Pelagic fauna.--For the purposes of discussing oil effects on individuals, pelagic fauna are divided into finfish, larvae of all marine organisms (except those few with benthic larvae) and pelagic crustaceans. Data on finfish toxicity (Table II.4.8) is not extensive and only a few species indigenous to the Gulf of Maine have been used in experiments. The data is not very conclusive, but an estimate of a toxic threshold of 5-50 ppm SAD seems reasonable, especially in light of the data reported by Wilber (1968). Because finfish avoid contaminated areas (Nelson-Smith, 1971), there has not been a strong interest in the toxic response of these organisms.

The toxic effects of oil on larval stages of many marine organisms have been much more extensively studied (Table II.4.9). Several investigators report that larvae appear to be 10-100 times more sensitive than adults (Mironov, 1968; Kuhnhold, 1970; Corner, et al., 1968). Typical concentrations of SAD causing lethal toxicity are .1-1 ppm. However, at the lower concentrations death may be a delayed response. Typically the larvae may develop abnormally, leading to death several weeks after exposure. In a non-laboratory environment, such maldeveloped individuals are much more susceptible to predation, competition and other secondary effects. It is also interesting to note that larvae tend to be more sensitive than eggs. Apparently, this is due to the protection afforded the embryo by the chorion.

Table II.4.10 summarizes the sparse data reported on the toxicity of pelagic crustaceans (shrimp and copepods). The critical concentrations may be somewhat lower than those for fish and 1-10 ppm SAD is probably the lower threshold. Smith (1968) suggests that because of the small size (a few millimeters) of many pelagic crustaceans, toxicity may be a function of size. That is, the larger individuals are possibly more resistant.

The benthic fauna are divided into four categories: gastropods (snails, limpets, etc.), bivalves (shellfish), crustaceans (shrimp, lobsters, etc.) and all others (worms, anemones, etc.). Apparently gastropods are the most resistant and crustaceans the most sensitive.

Most gastropods studied (Table II.4.11) indicate a rather high resistance to hydrocarbon toxicity, and the periwinkle (*Littorina littorea*), the common intertidal snail, is apparently very resistant. The critical concentration may be 100-200 ppm or more. Limpets (*Patella vulgata*) demonstrate the only significant deviation and appear to have a critical threshold concentration of less than 5 ppm. The relatively high resistance of gastropods may be due to secretion of a mucous substance (Shelton, 1971).

Bivalves, including oysters, clams, cockles and mussels are moderately resistant to oil (Table II.4.12). The ability to close their shells and seal off the ambient water mass acts as an effective protection mechanism. However, this closed condition cannot be maintained indefinitely and, in fact, cockles tend to "gape", making them more susceptible (Simpson, 1968). Typical critical concentrations for most bivalves is 5-50 ppm SAD.

Both benthic crustaceans and other miscellaneous benthic organisms (Tables II.4.13 and II.4.14) are apparently fairly sensitive to SAD. Threshold concentrations appear to be 1-10 ppm of SAD.

TABLE II.4.7 SUMMARY OF TOXIC RESPONSES FOR MARINE FLORA

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Phyto-Plankton	Dinobryon Sp. Peridinum Sp.	FIELD (freshwater pond, June-October)	N.S.O. crude 4.5 1/6" diam. test area (film on surface)		117 days (whole experiment)	growth suppressed	Kauss, et al (1972)	
"	Tabellaria Sp. Ankistrodesmus spirales	"	"		"	growth stimulated	"	
"	Fragillaria Sp. Ankistrodesmus falcatus	"	"		"	no response	"	volatilization & bacterial degradation
"	Chlorococcum Sp.	LABORATORY	Soluble extract from 50 ml in 1 liter water 0, 25, 50, 75, 100% "saturation	1-5 ppm 100% "saturation"	10 days	no response	"	
"	Cosmarium Sp.	"	"	"	12 days	growth inversely proportional to % saturation	"	
"	Chlorella vulgaris	"	Soluble extract from 50 ml "Gulf" crude in one liter water 0, 10, 25, 50, 75, 90% "saturation"	"	10 days	growth suppressed	"	suppression attributed to a decrease caused by oil
"	"	"	Benzene	25-500 ppm 500-1744 ppm	10 days 10 days	initial inhibition for 2 days, then growth lethal toxicity	"	4 day $LD_{50} \cong$ 650 ppm (our estimate from Kauss data)
"	"	"	Toluene	25-250 ppm 500 ppm	10 days 10 days	slight inhib. lethal toxicity	"	4 day $LD_{50} \cong$ 175 ppm (our estimate from Kauss data)
"	"	"	O-Xylene	25-50 ppm	10 days	slight inhib. lethal toxicity	"	4 day $LD_{50} \cong$ 70 ppm
"	?	"	7 Alberta crudes concentrations unknown		10 days	2 day inhibition then stimulation	"	
"	Chlorella vulgaris	"	Smiley Colville (an Alberta crude) soluble extract		10 days	slight inhibition over 10 day period	"	

TABLE II.4.7 SUMMARY OF TOXIC RESPONSES FOR MARINE FLORA (Cont'd)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Phyto-Plankton	Numerous Species	Laboratory	"oil" .00001-1.0 ml/l; most used .001-1. ml/l	(.01-1000. ppm)	5 days	death 1 ml/l. (1000 ppm) delayed cell division 1.0-.001 ml/l no effect .01-.001 ml/l (10-.01 ppm)	Mironov (1970)	does not describe oil used or whether concentrations quoted are soluble or not
Intertidal plants surf grass	*Phyllospadix torreyii*	incident Santa Barbara	weathered crude heavy coating		one tidal cycle	death through coating & abrasion (smothering)	Foster, *et al* (1971)	
Green algae (mid & high intertidal)	*Enteromorpha intestinalis*	"	heavy coating various coatings			slight damage except where completely coated	"	
	Chaetomorpha aerea	"	heavy coating various coatings					most intertidal algae have a mucous coat which sheds oil; high intertidal plants, where oil dried were damaged, season important- i.e. blooms, subtidal plants not affected
	Ulva californica	"	heavy coating various coatings			U. californica recovered in 4 months		
Brown algae	*Egregia laevigata*	"	various coatings			little damage		
Red algae	*Porphyra* sp.	"	"			killed-holds oil		
Kelp	*Macrocystis angustifolia*	"	heavy coating			no damage-mucous coat		
"	"	*Tampico Maru* Laboratory	diesel fuel .01%-1% emulsion	1-100 ppm	7 days	loss of photosynth. ability	North *et al* (1964)	*Tampico Maru* spill resulted in kills to members all phyla.
Salt marsh grasses	*Spartina townsendii*	Incidents: Milford Haven & Torrey Canyon	fresh crude		20 min. (M.H.) after spill	75-100% killed	Cowell (1971)	many other marsh plants studied but not summarized here
	Puccinellia maritima	weathered crude (& dispersants)			8 days (T.C.)			
Macrophytic algae		incident: Torrey Canyon	weathered crude & dispersants			algae increased coverage of rocks	Bellamy *et al* (1967)	oil & dispersants killed herbivores, so algae overgrew rocks

TABLE II.4.7 SUMMARY OF TOXIC RESPONSES FOR MARINE FLORA (cont'd)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Phytoplankton	Prasinophyceae Halosphaera sp. Pterosperma sp.	incident: Torrey Canyon	crude slick			lethal toxicity (reduced popula-tion)	Smith (1968)	Cysts (reprod cells) of these were disrupted by oil, since they float near surface
"	various species	Laboratory	BP 1002 emulsifier with-out kerosene	1.2×10^{-3} ppm 1.2 ppm		generation time & lag phase lengthened below 1.2 ppm lethal toxicity at 1.2 ppm	"	brackish water species better able to withstand membrane damage caused by emulsifier (sol'n in lipid layer)
Salt marsh grasses	various species	Field ex-periment (Milford Haven)	fresh crudes (Kuwait)			see p.31 of Cowell annuals most sus-ceptible, perennials most resistant	Baker (1971)	germination in annuals inhibited seasonally dependent
Kelp	Macrocystis angustifolia	Laboratory	benzene n-hexane toluene	10 ppm 10 ppm 10 ppm	96 hrs. 96 hrs. 96 hrs.	slight photosynth. inhib. no effect visible injury, 75% reduction in photosynth.	Wilber (1968)	

TABLE II.4.8 SUMMARY OF TOXIC RESPONSES OF FINFISH

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Atlantic Salmon	*Salmo salar*	Laboratory	Corexit 8666 1-10,000 mg/1 complete emulsion		7-14 days	4 day LD_{50} >10,000 mg/1	Sprague & Carson (1970)	authors point out probability of sublethal-long-term effects of oil dispersant at lower conc.
"	"	"	1-10,000 mg/1 complete emulsion BP1100 B BP 1100 Gulf agent 1009 Naphtha gas Dispersant 88 Dispersol SD BP1002 XZIT x-1-11	2-2000 ppm	7-14 days	4 day LD_{50} 1-100 mg/1		authors believe Corexit is microbially degraded; the byproducts of this process, either from Corexit or waste from microbes, are toxic after 7 day's building in test tank.
"	"	"	1-10,000 mg/1 temporary emulsion Bunker C	0-1 ppm	7-14 days	4 day LD_{50} >10,000 mg/1; 7 day LD_{50} ~ 2000 mg/1		
"	"	"	Bunker C & Corexit 8666		"	4 day, 7 day LD_{50} ≅100-1000 mg/1		
Flounder (winter)	*Pseudopleuronectes americanus*	"	Bunker C & Corexit 8666		"	4 day LD_{50} >10,000 mg/1; 7 day LD_{50} ~1000 mg/1		
fresh water fish	*Mugil saliens* *Sargus annularis* *Crenilabrus tenca*	Laboratory	"oil" .25 ml/1		"many days" "several days"	no effect	Mironov (1970)	emulsion more toxic than film
Plaice	*Rhombus maeoticus*	Laboratory	"oil" 10^{-4}-10^{-5} ml/1		2 days	lethal toxicity to eggs	"	
Shad	*Alosa sapidissima*	Laboratory	Gasoline #2 Diesel fuel Bunker C			LD_{50} [hr.: 24 48 96] Gas 91 91 -; #2 204 167 -; C - 2,417 1,952	Tagatz (196)	loss of toxicity by evaporation
Mullet	*Mugil cephalus* *Micropogon undulatus*	Laboratory	#2 Diesel oil .01-10% emulsified	.002-2 ppm	LD_{50} (48 hr.) 420 ppm (acute) LD_{50} (chronic) 42 ppm	LD_{50} (48 hr.) ~420 ppm (acute) LD_{50} (chronic) 42 ppm	Texas Instruments (1971)	safe at 4.2 ppm

TABLE II.4.8 SUMMARY OF TOXIC RESPONSES OF FINFISH (Cont'd)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Roach	<u>Rutilus</u> sp.	Laboratory	cyclohexane benzene methylcyclohexane	10 ppm 10 ppm 10 ppm	3-4 hrs.	lethal toxicity	Nelson-Smith (1970)	
Sunfish		"	Phenanthrene Naphthalene Xylene, toluene benzene, ethylene	4-5 ppm 4-5 ppm 22-65 ppm	1 hr.	lethal toxicity	Wilber (1968)	
Thread herring	<u>Ophistonema onglimum</u>	incident: Ocean Eagle San Juan	crude oil & emulsifiers			95% of schools near spill had lesions	Cerame-Vivas (1968)	

TABLE II.4.9

SUMMARY OF TOXIC EFFECTS OF OILS ON LARVAE AND EGGS OF MARINE ORGANISMS

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Plaice	Rhombus maeoticus	Laboratory	"oil" 10^{-4} - 10^{-5} ml/1			40 to 100% hatched pre-larvae perished	Mironov (1968)	no information on experimental methods
Barnacle	Balanus sp.					Larvae 100 times more sensitive than adults	"	"
Cod and Flounder		Laboratory	Bunker C film - 100 ppm	∿0	96 hours	35% pulled in stagnant water, not affected in running water	James (1926) reported in Kuhnhold (1970)	"
Black Sea Turbot		Laboratory	10-100 ppm dispersion of Russian crude	.01 - 1 ppm	2-3 days	100% eggs killed	Mironov (1967) reported in Kuhnhold (1970)	"
Herring		Laboratory	10^3 and $2x10^4$ppm film		2.5-3.5 days	100% eggs killed	Kuhnhold (1969) reported in Kuhnhold (1970)	"
Cod	Gadus morrhua	Laboratory	extract of Venezuelan oil in water 10^4ppm 10^2ppm extracts of Iranian crude 10^4ppm 10^3ppm 10^2ppm control	 .10ppm .1ppm 10ppm 1ppm .1ppm	100 hours	40% higher mortality than control 10-20% increase in mortality 99% killed 63% killed 33% killed 21% killed	Kuhnhold (1970)	Libyan (high paraffin content) did not cause increases in mortality; 10 day old larvae less sensitive
Cod	Gadus morrhua	Laboratory	extracts of Iranian Crude in water 10^4ppm 10^3ppm 10^2ppm 10^3plus 10-100ppm Correxit 7664 10-100ppm Correxit 7664	 10ppm 1ppm .1ppm control 100-1000ppm ∿0	1-10 days 4.2 days 8.4 days 14 days 14 days 3 to 6 hours no effect	Time to death for larvae exposed for 1 day	"	Young larvae less resistant than embryo; Herring less resistant; Plaice more resistant; Libyan crude affected larvae more than embryos.

TABLE II.4.9

SUMMARY OF TOXIC EFFECTS OF OILS ON LARVAE AND EGGS OF MARINE ORGANISMS (Cont'd)

COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Plaice	*Pleuronectes platessa*	Laboratory	0 - 10ppm BP1002	0 - 2ppm	1 - 30 days	10ppm BP1002 killed 100%; 2.5ppm BP1002 reduced survival by 50%	Wilson (1970)	see original article for considerable more detail; some mortality delayed due to effects on feeding and larval development
Barnacle	*Elminius modestus*	Laboratory	0 - 100ppm BP1002 1000ppm Kuwait	0 - 20ppm 1ppm	various	0 - 3ppm BP1002 increase mortality some reduction of activity	Corner, et al. (1968)	original article contains much more data on other dispersants and other tests; adults resistant up to 100ppm BP1002
Pilchard	*Sardina pilchardus*	Torrey Canyon Incident	Kuwait and emulsifiers			50-90% of eggs in plankton tows dead	Smith (1968)	
Lobsters	*Homarus americanus*	Laboratory	.001 - .1ml/l Venezuelan crude	(.01-1ppm)	24 - 96 hours	$96LD_{50}$ = .03 - .002ml/l	Wells (1972)	.001ml/l had little effect; .1ml/l very toxic
Sea Urchin	*Strongylocentrotus purpuratus*	Laboratory	extracts of 25ml crude and bunker C oils in 500ml sea water 6.25% - 50% dilutions	(.1-1ppm)		fertilization not affected; lowest dilutions interfere with fertilized egg development	Allen (1971)	Urchins generally very sensitive
Polychaete	*Sabellaria spinulosa*	Laboratory	.5 - 1ppm BP1002	.1 - .2ppm	several hours to several days	1ppm caused 100% mortality; .5ppm caused abnormal development	Wilson (1968)	death definitely due to kerosene solvent in BP1002
Crustaceans	several	Laboratory	1 - 10ppm BP1002	.2 - 2ppm		1ppm BP1002 lethal	Portmann & Connor (1968)	Larvae 10-100 times as sensitive as adults
Oysters	*Crassostrea gigas*	Laboratory	various detergents 0 - 3ppm	0 - .5ppm	24 hours	3ppm of all detergents toxic	Smith (1968)	also similar results for many other marine invertebrate larvae

TABLE II.4.10 SUMMARY OF TOXIC RESPONSES TO OILS OF PELAGIC CRUSTACEANS

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Copepod	several species	Laboratory	.001-.1 ml/l "oil"	(possibly 1-100 ppm)		insensitive to .001 ml/l, 100% death with .1 ml/l	Mironov(1969), cited in Mironov (1970)	experimental methods not described
Shrimp	<u>Penaeus</u> sp. <u>Palaemonetes</u> sp.	Laboratory	crude oil plus emulsifiers (1-100 ppt)	(1-100 ppm)		48LD$_{50}$ = 1-40 ppt crude oil 48LD$_{50}$ = .5-5 ppt crude plus Corexit	Mills and Culley (1971)	see reference for detailed breakdown; oils with higher proportion of aromatics most toxic
Copepod	<u>Calanus finmarchicus</u>	Laboratory	1-50 ppm BP 1002 Gamlen Dasic Molyslip Houghton Solvent 112	.2-10 ppm	1 hour-3 days	50 ppm detergent caused 100% mortality in an hour; 5-10 ppm detergents caused high mortality in 3 days; 1 ppm was injurious	Smith (1968)	
Copepod	<u>Acartia clausi</u>	Laboratory	5-100 ppm BP 1002 Dasic	1-20 ppm	10-1000 minutes	lethally toxic at all concentrations	"	BP 1002 5 times as toxic as Dasic; <u>Acartia</u> much less resistant than <u>Calanus</u>; suggests small animals toxicity is related to size
Pink Shrimp	<u>Pandalus montagui</u>	Laboratory	BP1002		48 hr. LD$_{50}$ = 5.8 ppm	Portmann and Connor (1968)		

TABLE II.4.11 SUMMARY OF TOXIC RESPONSES OF GASTROPODS

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Dog Whelk Periwinkle	Nucella lapidus Littorina littorea	Incident	"dispersants"			more resistance than crustaceans	Shelton (1971)	Gastropods can produce copious mucus secretion
Periwinkle	Littorina littorea	Incident: Arrow	Bunker C			ingestion of oil-no effect	Scarratt et al (1970)	intertidal contact with oil-oil passed through digestive system unmodified - no uptake in other organs
Periwinkle	Littorina littorea		fresh crude oil			"sensitive"	Nelson-Smith (1967)	
Limpets	Acmea sp.	Incident: Santa Barbara	weathered crude oil	heavy coat		little damage	Foster, et al (1971)	limpets appeared to be feeding on oil
Periwinkle " Limpet Dogwhelk	Littorina neritoides Littorina saxatilis Patella vulgata Thais lapillus Gibbula umbilicalis Littorina obtusata	Field	Kuwait crude (fresh) Kuwait crude (weathered) BP 1002 (single in combination) ~ 2 liters/m²		5 min.-6 hrs.	general relative toxicity to gastropods BP 1002 > fresh ≫ weathered	Crapp in Cowell (1971)	data difficult to summarize by species; experiments were small scale and contained many uncontrolled variables, making quantification of results difficult
same 6 species as above		Laboratory	BP 1002 BP 1100			toxicity dependent on season: least toxic in winter (water temp. 10°C) highest in summer (water temp. 18°C) BP 1002 much more toxic than BP 1100	"	same comments as above
Limpet Periwinkle Periwinkle	Patella vulgata Littorina littorea Littorina littoralis	Laboratory	various crudes		sprayed on for 1 hr. then washed	1-89% mortality for L. littoralis L. littorea very resistant. P. vulgata very sensitive	Ottway in Cowell (1971)	high mortality correlates with asphaltenes & low boiling compounds (aromatics, especially).

TABLE II.4.11 SUMMARY OF TOXIC RESPONSES OF GASTROPODS
(cont.)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Periwinkle	Littorina littorea	Laboratory	BP 1002		24 hrs.	LD_{50} ~100 ppm	Smith (1968)	intertidal species periwinkles may recover from 100 ppm all detach from substrate before dying
Dog Whelk	Nucella lapillus		0-100 ppm	0-20 ppm	"	LD_{50} ~100 ppm		
Top-shell	Monodonta lineata					LD_{50} = 100 ppm		
Limpet	Patella vulgata					LD_{50} = 5 ppm		
Limpet	Patella vulgata	Laboratory	BP 1002			96h LD_{50} = 5 ppm	Perkins in Carthy & Arthur (1968)	data supports Ottway's conclusions
			0-200 ppm	0-400 ppm				
Periwinkle	Littorina littoralis	Laboratory	BP 1002			24h LD_{50} = 250 ppm		
Periwinkle	L. littorea	"	"			24h LD_{50} =2000 ppm		
Periwinkle	L. littorea	"	crude oil weathering BP 1002			weathered oil less toxic than oil & BP 1002		oil weathered for 24h in lab. simulated tidal washing in lab.

TABLE 11.4.12

SUMMARY OF TOXIC EFFECTS OF OIL
ON MARINE BIVALVES (SHELLFISH)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Cockles	*Cardium edule*	Laboratory	detergents	0-20 ppm	variable	$48LD_{50}$ for BP1002 81ppm	Portmann & Connor (1968)	$48LD_{50}$ for many detergents given
Mussel	*Modiolus modiolus*	Field (Arrow Spill)	Bunker C			oil content 100-125 μg/gm	Scarratt, *et al.* (1970)	Incorporation of Bunker C after Arrow Spill
Mussel	*Mytilus edulis*	Laboratory	BP1002	∿.4ppm		$24LD_{50}$ = 90ppm $48LD_{50}$ = 2ppm	Perkins (1968)	
Cockle	*Cardium edule*	Laboratory	BP1002	∿.4ppm		$24LD_{50}$ = 20ppm	Perkins (1968)	
Mussel	*Mytilus edulis*	Laboratory	0-100ppm BP1002	0-20ppm	24 hours	5ppm BP1002 not lethal in 24 hours; 10ppm BP1002 lethal	Smith (1968)	Also obtained information on sublethal concentrations
			1000ppm crude emulsion	∿60ppm	24 hours	no deaths, but mussels could not attach properly		
Razor clam Queen scallop	*Ensis siliqua* *Chlamys opercularis*	Laboratory	BP 1002			24 hrs. LD_{50} = 0.5 ppm 24 hrs. LD_{50} = 1 ppm	"	subtidal species
Oysters		Laboratory	BP1002	∿2-20ppm		10-100ppm BP1002 lethal	Simpson (1968)	
Cockles	*Cardium edule*		phenol			$48LD_{50}$ = 500ppm	Nelson-Smith an Hepple(1971)	
Mussel	*Mytilus edulis*	Laboratory	"laboratory" weathered (24 hours) Arabian crude plus Correxit or Dispersol approximately .5ml/m^2 + 10% dispersant		4 tidal cycles	no toxicity for crude oil only; 50% mortality with Dispersol plus oil		simulated tidal conditions

TABLE II.4.12 (Cont.)

SUMMARY OF TOXIC EFFECTS OF OIL ON MARINE BIVALVES (SHELLFISH)

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTIONS	DURATION	RESPONSE	REFERENCE	REMARKS
Mussels	<u>Mytilus californianus</u>	Laboratory	$0-10^5$ ppm Santa Barbara crude (as surface film)	0-100ppm	34 days	10^4 and 10^5 ppm caused significant mortality	Kanter, Straughan, and Jessee (1971)	individual from area (Coal Point) subject to natural seeps possibly less susceptible than those from other areas; data not conclusive
Mussels	<u>Mytilus edulis</u>	Laboratory	1000mg/l mineral oil (paraffin only)	0	up to 6 days	no mortality	Lee (1972)	primarily an experiment to investigate uptake and incorporation
			1-8mg/l heptadecane	0	up to 6 days	no mortality		
			100ppm tetralin	100ppm	up to 6 days	toxic		
			1ppm toluene, napthalene, 3,4-benzpyrene	1ppm	up to 6 days	not toxic		

TABLE II.4.13

SUMMARY OF TOXIC EFFECTS OF OIL ON MARINE BENTHIC CRUSTACEANS

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDRO-CARBONS IN SOLU-TION	DURATION	RESPONSE	REFERENCE	REMARKS
Shrimp	Crangon crangon	Laboratory	various emulsifiers	~1ppm	48 hours	48LD$_{50}$ for BP1002=3.8ppm	Portmann and Connor (1968)	
Shore crab	Carcinus maenas	Laboratory	various emulsifiers	~3ppm	48 hours	BP1002 48LD$_{50}$=15ppm		
Lobster	Homarus gammarus	Laboratory	various emulsifiers	~4ppm	48 hours	BP1002 24LD$_{50}$=20ppm		
Barnacles	Elminius modestus	Laboratory	1-100ppm BP1002	0-20ppm	48 hours	100% mortality with 100ppm; 5ppm shows sub lethal effect	Corner, et al. (1968)	
			100ppm film of Kuwait	.1ppm	24 hours	some inhibition of cirral beat		
Lobsters	Homarus americanus	Laboratory	Bunker C and various disper-sants		7-14 days	4 day LD$_{50}$ for Bunker C > 10,000 ppm	Scarratt et al (1970)	lobster fishery of Chedabucto Bay not damaged by Arrow spill; lobsters considered very resistant
Barnacles	Balanus balanoids	Laboratory	BP 1002	2 ppm		100% survival at 10ppm	Perkins (1968) in Carthy & Arthur (1968)	
Hermit Crab	Eupagurus bernhardus	Laboratory	BP 1002	1ppm		96 hours LD$_{50}$ = 5ppm		
Crab	Carcinus maenas	Laboratory	BP 1002	6ppm		96 LD$_{50}$ = 30ppm		
Crab	Cancer pagurus	Laboratory	BP 1002	2ppm		24LD$_{50}$ = 10ppm	Smith (1968)	
Shrimp	Crangon vulgaris	Laboratory	BP 1001	4ppm		24LD$_{50}$ = 2ppm		
	Carcinus maenas	Laboratory	BP 1002	5ppm		24LD$_{50}$ = 25ppm		
Hermit Crab	Diogenes pugilator	Laboratory	BP 1002	5ppm		24LD$_{50}$ = 25ppm		
Barnacle	Balanus balanoides	Laboratory	crude oil	2ppm		2% is toxic	Nelson-Smith in Hepple (1971)	
many species		Field	Kuwait BP 1002				Crapp in Cowell (1971)	many field experiments and data which is difficult to summarize; data in-dicates little toxic response of most species to weathered kuwait.

TABLE II.4.14 SUMMARY OF TOXIC EFFECTS OF OIL ON OTHER BENTHIC INVERTEBRATES

ORGANISM COMMON NAME	SCIENTIFIC NAME	EXPERIMENT TYPE	SUBSTANCE & REPORTED AMOUNT	ESTIMATED HYDROCARBONS IN SOLUTION	DURATION	RESPONSE	REFERENCE	REMARKS
Polychaete annelid	Arenicola marina	Laboratory	BP 1002	6 ppm		96 hr. LD_{50} = 30ppm	Perkins in Carthy & Arthur (1968)	
"	Nereis diversicolor	"	BP 1002	5 ppm		24 hr. LD_{50} = 25ppm	Smith (1968)	
starfish	Asterias rubens	"	BP 1002	6-8 ppm		24 hr. LD_{50} = 40 ppm 96 hr. LD_{50} = 30 ppm	Perkins in Carthy & Arthur (1968)	
Anemones	2 species	"	"	5-10 ppm		24 hr. LD_{50} = 25-50ppm	Smith (1968)	
starfish	A. rubens	"	"	5 ppm		24 hr. LD_{50} = 25 ppm	"	
Brittlestar	Ophiocomina nigra	"		1 ppm		24 hr. LD_{50} = 5ppm	"	
Coelenterate	Tubularia crocea	"	crude 0.1-5%			"quickly lethal"	Nelson-Smith in Hepple (1971)	
"	Calliactis parasitica	"	BP 1002	5 ppm		24 hr. LD_{50} = 25	Smith (1968)	
Sandworm	Nereis virens	"	"BP"			96 hr. LD_{50} = 165ppm	LaRoche et al (1970)	only code names of 10 dispersants are given. Sandworm is one of most valuable marine products in New England
"	"	"	"crude oil B"	0		96 hr LD_{50} = 6100ppm		
Polychaete annelids	Cirriformia tentaculata	Incident: shore terminal spill	fresh fuel oil coating on mud surface			little damage	George (1970)	Mucus secretions of worms and inability of oil to penetrate mud may have prevented toxicity
"	"	"	fuel oil & Essolvene			high mortality	"	oil may have been dispersed into mud by emulsifier and ingested by worms
"	"	Laboratory	BP 1002 Essolvene Corexit 7664		24 hrs.	24 hr. LD_{50} (ppm) BP / Essolvene / Corexit C. tentaculata 30 / 63 / 100,000 C. cirratus 129 / 162 / 100,000		
Coral	several species	Laboratory	Corexit (0-500 ppm) crude oil 0-500 ppm (slick) & mixtures			harmful at 100-500 ppm (not necessarily completely in solution) dispersant more toxic than oil	Lewis (1971)	crude oil concentrations given were not completely dissolved

Table II.4.15 summarizes the toxicity data. For each group of organisms the estimated range of critical concentrations for various petroleum substances is shown. The estimates of #2 fuel oil and fresh crude are based on information summarized in Table II.4.5.

Sub-lethal effects on behavior.--Most marine organisms depend upon a complex set of behavioral characteristics to maintain a normal life pattern. Many of these behavioral patterns, especially feeding and reproduction, involve communication based on chemical clues called pheromones. Chemical communication has been extensively studied in insects, but only recently has significant attention been given to marine animals. However, sufficient information is available to draw tentative conclusions regarding the possible effects of oil on chemical communication.

Early studies by several investigators (see Hasler, 1970) focused on migration habits and territory recognition by fish, especially salmon. More recent work has focused on feeding, reproduction and social behavior in fish and lobsters (Todd et al., 1972). In addition, Whittle and Blumer (1970) have investigated the role of pheromones in predation by starfish. Extrapolation of the results of these laboratory experiments to natural environments is extremely difficult (probably more so than toxicity tests). The objective of the experiments is to assess behavioral characteristics; however, the organisms are placed in very "unnatural" environments,* which likely disrupt behavior in themselves. In addition, the chemical clues are apparently extremely subtle and occur in very low concentrations, which makes actual identification difficult. Introduction of foreign substances may in fact block these communication signals, but the foreign chemicals may also induce other

---

*Todd et al. (1972) have attempted to alleviate some of these problems by using large aquariums and several species of organism simultaneously.

TABLE II.4.15

Class of Organisms	Estimated Typical Toxicity Ranges (ppm) for Various Substances			
	SAD[1]	#2 Fuel Oil/Kerosene	Fresh Crude	Weathered Crude
Flora	10-100	50-500	$10^4 - 10^5$	Coating More Significant than Toxicity
Finfish	5-50	25-250	"	
Larvae	.1-1.	.5-5	$10^2 - 10^3$	
Pelagic Crustaceans	1-10	5-50	$10^3 - 10^4$	
Gastropods	10-100	50-500	$10^4 - 10^5$	
Bivalves	5-50	25-250	"	
Benthic Crustacaens	1-10	5-50	$10^3 - 10^4$	
Other Benthic Invertebrates	1-10	5-50	$10^3 - 10^4$	

1 - Soluble aromatic derivatives (aromatics and napthenoaromatics)

behavioral responses, only indirectly disrupting normal communications.

The most remarkable part of the utilization of pheronomes is that they are recognized at extremely low concentrations. Whittle and Blumer (1970) found starfish react to oyster extracts in concentrations of parts per billion. Sea lamprey can respond to specific chemicals (amines) at 20 parts per billion, hydra and coelenterates respond to glutathiore at 30 ppb, and eels recognize β-phenylethyl alcohol at concentrations on the order of molecules. Clearly some marine animals have extremely sensitive olfactory and taste organs. More remarkable is the specificity of the animals' response, being able to differentiate among a myriad of compounds in sea water. The apparent reliance on the ability to differentiate between chemical clues raises serious questions about the effect of blocking of the chemical receptions, the masking of chemical clues, and the substitution of "false" chemical clues.

One of the most significant sets of studies has been carried out by Todd et al. (1972), examining the bullhead fish,which has an extremely complex set of social behaviors. The bullhead is capable of differentiating between species and can even recognize individual fish - making pairing relationships possible. Many fish which live in schools have no individual relationships or social structure. The bullhead lives in communal life with clear social functions among dominant and subordinate individuals. (Todd attributes this highly complex behavior to subtle chemical clues.)

Todd has found that the bullhead brain has enlarged olfactory (smell) lobes and performs a highly integrative function for the senses. Other fish have less developed olfactory areas, and less complex behavior. He concludes that complex behavior is related to a highly developed capability of smell; taste is basically utilized for feeding function. To test this hypothesis the olfactory and the taste organs were destroyed and the bullhead's behavior analyzed. The results show that the bullhead suffered marked loss of the capability of social behavior (mates were attacked and unrecognized) when the olfactory area was destroyed. This indicates significant dependence on chemical clues to maintain complex behavior.

In experiments with lobsters, Todd found that lobsters were attracted and then repulsed by soluble aromatic components of kerosene but that straight-chained paraffins noticeable influence. Kerosene and the branched and cyclic paraffins induced searching and feeding behavior. Kerosene, polar aromatics, and branched cyclic fractions also initiated agitated grooming behavior. Conceivably lobsters could be attracted to an oil spill because of the polar aromatic component and the other components of crude oil could disrupt social organization and individual behavior patterns, or even cause lethal or sub-lethal effects from exposure.

Todd has postulated an inverse relationship between physiological toughness and behavioral complexity, i.e. the more complex the behavior patterns for a fish the lower the adaptability (resistance) to stress (pollution). The most complex behavioral species will have difficulty producing highly resistant strains in a stressed area, i.e. the adaptation of these species will take place but not as successfully as species with simpler (less complex) behavior patterns. Moreover, Todd expresses the proposition that there is a relationship between increased behavioral complexity and ecological complexity. The most complex behavioral species appear in the most stable, mature, i.e. diverse, ecosystem. Therefore he postulates the vulnerability of an ecosystem to stress is related to behavioral complexity, i.e. there is increased vulnerability of an ecosystem with increasing numbers of behaviorally complex species which can only appear in mature ecosystems.

The validity of these conclusions is uncertain without more data. It is evident that individual species dependent upon many chemical clues to maintain complex behavior are particularly vulnerable (if Todd's experiments can be generalized), but there is no indication that they are less able to adapt over time to environmental changes than less behaviorally complex species. In fact, population and community level survival may be enhanced due to behavioral complexity. A mature ecosystem typically contains behaviorally complex species which is usually more diverse and stable. Thus, while it may contain a larger number of individually vulnerable species, the mature ecosystem, because of its diversity of animals and plants, should be better able to absorb stress than less mature, i.e. less diverse system.

In reviewing the field of chemical communication in marine organisms, and assessing their vulnerability to crude oil a few conclusions can be drawn. However, they must be tempered with the realization that the field is not extensively developed and most of the experiments are preliminary. Field conditions may considerably alter behavioral responses and circumstances of exposure, thus either enhancing or diminishing effects while revealing new problems. Moreover, higher boiling hydrocarbons have not been used in any experiments, and it is this portion of crude oil that is the long-term contaminant of the environment.

Apparently, disruption can occur from relatively low concentrations of petroleum substances (10-100 ppb). However, the toxic properties of the low boiling component may be more important than the chemical communication disruption. More importantly, it is unclear whether the behavioral changes that might occur can lead to permanent damage to individuals and populations.

The extent of chemical communications in marine animals is substantial and plays an essential role in behavior. Although the present evidence for the effects of crude petroleum on chemical communication is limited, the problem in terms of long-term effects related to successful adaptation or survival could be serious. Any introduction of large quantities of hundreds of chemical compounds should be a cause for concern, requiring both accelerated experimentation examining possible consequences and a sense of caution in decision-making regarding any new possible mode of releases into the marine environment.

Incorporation of hydrocarbons.--The most important effect of oil on marine organisms from the point of view of public health is the incorporation of hydrocarbons in food chains. There is ample evidence that a variety of marine organisms do, in fact, incorporate and accumulate hydrocarbons (Blumer, 1970; Lee, 1972; Zobell, 1971). Incorporation of hydrocarbons themselves apparently does not affect the organisms directly. However, two problems are important to man: (1) accumulation in organisms of polycyclic aromatic hydrocarbons, especially carcinogens; and (2) tainting of edible species.

The introduction and dispersal of carcinogenic compounds into the environment has been of increasing general concern over the last few decades. Besides the increase of lung cancer related to air pollution and smoking, there has been a steady rise in many types of cancer in the U.S. and other industrialized countries. While much of the increase can be attributed to successful prevention and treatment of other formerly fatal diseases--influenza, typhoid, tuberculosis--and the consequent increase in life span and the older population, part is related to increasing environmental contaminants from a number of sources - automobiles, industrial waste, food additives, etc. Crude petroleum and its fractions contain hundreds of compounds, most of which are not carcinogenic. However, petroleum also contains polycyclic aromatic hydrocarbons (PAH) and other individual compounds, some of which are proven carcinogens.

Cancer and polycyclic aromatic hydrocarbon compounds.--Polycyclic aromatic hydrocarbons (PAH) are multi-ring aromatic compounds. The most carcinogenically active compounds are found in substituted tri (3) and tetra (4) cyclic aromatic hydrocarbons. Some penta (5), hexa (6) and higher cyclic compounds are also included. PAH were identified as the active carcinogens in petroleum and coal products and residues, e.g. petroleum asphalt, coal tar, soot, lubricating oils, which caused increased incidents of skin cancer in exposed workpeople. It was found that oil containing more than 0.03% polycyclic aromatic hydrocarbon (PAH) with 4 or more rings caused cancer. (Gerarde, 1960)

The carcinogenic properties of polycyclic aromatic hydrocarbons are attributed in part to the presence of certain chemical structures in the compound. The mode of action appears to be chemical rather than physical and may relate to the properties of hydroxylyzed metabolites (compounds formed from the original compound) or mutagenic (mutation-causing ability) properties of carcinogens or their metabolites to disrupt cellular growth. Given the specific properties needed for carcinogenic activity, it is important to ascertain whether these compounds are changed in the food chain, and if they are, into what products.

PAH carcinogens occur naturally in a variety of plants, and are distributed throughout the food chain. Fresh water algae have been found to synthesize a variety of PAH carcinogenic compounds. Algae *Chlorella vulgaris*, which synthesizes several PAH's, was found to contain 10-50 μg/kg (dry weight) of PAH compounds. Apparently PAH carcinogens are growth stimulants in plants, and their carcinogenic potency appears to be related to their growth stimulating power. PAH have been found to increase ten to one hundred-fold after germination in higher plants. In phytoplankton, production of aliphatic and aromatic hydrocarbons, including carcinogenic PAH's, may be as much as three tons per year per square kilometer. Anaerobic bacteria synthesize appreciable quantities of hydrocarbons including 3, 4-benzpyrene, 1, 2-benzathrene, 3, 4 and 10, 4-benzfluoranthene. Specifically, the bacteria Clostridium putride assimilates lipids of dead plankton and forms 120 to 800 μg benzpyrene (BP) per kilogram of plankton material (dry weight). Thus, a large number of "natural" sources of carcinogenic compounds exist, confusing the distinction between "natural" or contaminated areas.

The wide distribution resulting from natural and man-made sources is illustrated by benzpyrene (BP), an extensively studied carcinogen (Zobell, 1971). BP has been found in marine sediments, fish, shellfish, and plankton in both contaminated (Europe and American) and uncontaminated (Greenland) areas. Blumer found 40-1300 μg/kg BP in soil that he considered uncontaminated. Table II.4.16 shows the range of concentrations of BP for a variety of marine animals, plants and sediments, and other categories. The uncontaminated general level of food is put at 10-20 μg of BP per kilogram (dry weight). Although most concentrations of BP in the environment are low, contamination of sediment can reach 5 ppm, and in marine animals about 1/10 that level. From Table II.4.16 the presence of BP in the sediment and marine flora and fauna in the same area is indicated, thus demonstrating that contamination of the sediment may lead to contamination of marine organisms. However, significant concentrations are also found in organisms from uncontaminated areas such as the coast of Greenland. In discussing the distribution of BP in the environment, it should be remembered that it constitutes only a variable portion of the total PAH present, perhaps

Table II.4.16

Quantities of 3,4-benzpyrene Detected in Marine Animals and in Bottom Deposits. (Zobell,1971)

Kind of animals	Geographic location	BaP, μg/kg
Oysters	Norfolk, Virginia	10 to 20
"	French coast	1 to 70
Mussels	Toulon Roads, France	2 to 30
Holothurians	Villefranche Bay, France	up to 2000
"	West coast of Greenland	nil
Codfish and shellfish	" " " "	16 to 60
Fish nad shellfish	Saint-Malo Bay, France	3 to 125
Fish and crustaceans	Villefranche Bay, France	nil to 400
Crustaceans	Arctic Ocean	nil to 230
Isopod crustaceans	Clipperton Lagoon	up to 530
Various fishes	Adriatic Coast, Italy	nil to 900
Invertebrates	" " "	nil to 2200
Material	**Geographic location**	**BaP , μg/kg**
Mud (42 stations)	Tyrrhenian Sea	1 to 3000
Mud from pyster beds	French coast	90 to 2840
Mud (17 stations)	Mediterranean coast	up to 1800
Mud (8 stations)	Villefranche Bay, France	16 to 5000
Mud (12 stations)	French coast	nil to 1700
Mud and sand	Villefranche Bay, France	nil to 1700
Calcareous deposits	Franch coast	8 to 59
Surface mud	Italian coast	nil to 2500
Mud (218 samples)-	Adriatic coast	nil to 3400

1-20%. Therefore, low concentrations of BP are deceptive if they are interpreted to indicate low accumulations of PAH without other confirming analysis.

There are a number of general sources of PAH hydrocarbons including oil spills, coal tar, petroleum asphalt, and cooking oil. Crude petroleum has been found to contain a number of carcinogenic PAH compounds including 1, 2-benzanthrene, chrysene, triphenylene, 1, 2-benzphenanthrene, phenanthrene, and dibenzthiophene. Various crudes have been analyzed for their content of BP and a range of values from less than 0.1 ppm to more than 1 ppm has been found. Naphthenic and asphalt-based petroleum contain more quantities of carcinogenic PAH's than paraffin-based crudes because the greatest proportion of those crudes is made up of high molecular weight hydrocarbons. It should be noted that the relative proportion of carcinogens per kilogram of crude will increase after weathering removes low boiling fractions. Zobell (1971) estimates that a spill of 3 million gallons of oil could contain 100-200 lbs. of carcinogenic material.

PAH compounds are very insoluble. Their solubility is increased by the presence of detergents or non-colloidal hydrocarbons (purines, acetone) but the concentration of the detergents needed to achieve these increases is unrealistic, especially in marine environment. Therefore the primary mode of distribution of PAH hydrocarbons is adsorption (adherence) onto particulate matter.

The clearest evidence for the absorption of PAH compounds is from a study by Lee et al. (1972). They found that the marine mussel <u>Mytilus edulis</u> incorporated a number of hydrocarbons including 3, 4-benzpyrene. However, most of the compounds remained in the gut, indicating a lack of absorption into the body. BP is excreted, but some remains even after removal from the source of contamination. Apparently, unlike mammals and bacteria, no substantial degradation of PAH compounds takes place in mussels, copepods and fish once absorbed into the tissue. This poses the problem of accumulation of PAH carcinogens even if little is absorbed at one time through the digestive system. Thus, crude petroleum spilled into the environment, even if only slightly soluble, or carried on particulate matter, might accumulate in edible fish and shellfish. However, Lee et al. (1972) indicate that there may be a maximum accumulation concentration in mussels.

The oxidation of BP and other PAH carcinogens occurs in the presence of sunlight. However, degradation is slower in oil than in aqueous solution. Therefore much of the PAH compounds will be protected from easy oxidation, and this process is likely to be comparatively slow. Another route is degradation by bacteria from water and soil. The lack of nutrients, especially phosphorous and nitrogen compounds, may reduce the extent of degradation. Finally, some animals metabolize carcinogenic hydrocarbons, but marine organisms in general do not seem to possess this ability.

The clearest indication of the length of time necessary for effective degradation comes from the work of Blumer et al. (1972) on stranded crude oil. The reduction of various types of compounds in oil over a period of years was examined. Only slight degradation of PAH compounds occurred. Though theoretically it is possible to oxidize and microbially degrade the PAH compounds in crude oil, two factors cause the half-life of the compounds to be in years. First is the preference of bacteria to degrade normal paraffins, branched paraffins, and cycloparaffins in that order before they attack PAH compounds. The second is that despite the considerable ability of bacteria to rapidly degrade these compounds, optimum environmental conditions rarely exist to allow these rates to be attained.

In summary, PAH carcinogens tend to remain in the environment capable of being adsorbed on particulate matter or absorbed by burrowing animals, and thus provide routes to enter the food chain. Edible fish and shellfish can partially absorb these compounds through their gut tract. Marine animals do not appear to metabolize them to a significant degree when they enter their tissues. Potentially slow accumulation can occur; moreover, ample evidence is available to show this process does indeed occur for a number of fish and shellfish.

Although man does not absorb PAH to any substantial extent through the gastrointestinal tract (Gerarde, 1960), even a small absorption of these compounds into the body or incorporation in the gastrointestinal tract presents a danger of inducing cancer, especially in light of the medical judgement that prolonged low-level exposure to carcinogens can be the most effective way of producing cancer. Although the human body does metabolize these compounds, initially by hydroxylation, it is still uncertain whether the metabolites are themselves carcinogenic. Thus an increase in exposure would constitute an increased health danger.

Tainting.--Tainting of marine organisms also results from incorporation of hydrocarbons. However, rather than only PAH's causing the problem, all fractions, especially soluble low boiling fractions, may cause tainting. Numerous investigators have reported data relating to tainting (Blumer and Sass, 1970; Lee et al., 1972; Mackin, 1961; Nelson-Smith, 1971; Tarzwell, 1971; Wilder, 1970; and Sidhu et al., 1970).

Filter feeding organisms, especially bivalves and some finfish, such as mullet, are particularly susceptible to tainting. Nelson-Smith (1971) reports that concentrations in water as low as .01 ppm of crude oil cause tainting in oysters. Experiments by Wilder (1970) indicate that lobsters become tainted only by immersion in sea water containing oil, but not from eating oil-coated food. This is particularly significant, because it indicates that incorporation of hydrocarbons in the food chain may result from direct removal from sea water and not from feeding and ingestion of food containing petroleum substances. Burns and Teal (1971) report that #2 fuel oil spilled in a salt marsh was incorporated by nearly all the organisms in the marsh ecosystem.

The concentration threshold for the development of objectionable taste in animal tissue is in the range of 5-50 ppm (McKee and Wolf, 1963). However, gas chromatography (Blumer, 1970) is capable of detecting concentrations at much lower values (ppb range). Data from Lee et al. (1972) indicate that for various types of hydrocarbons there may be maximum amounts that will be incorporated by a particular organism. For the mussel Mytilus edulis he found that aromatic hydrocarbon concentrations in the organisms may reach 70 ppm (dry weight basis). Blumer and Sass (1970) reported concentrations of hydrocarbons from 5-70 ppm (wet weight) in various shellfish heavily contaminated by a #2 fuel oil spill. The data from Lee also indicates the efficiency with which filter feeders remove hydrocarbons from seawater. Significant levels of hydrocarbons could be detected in the organisms within 2-4 hours after placement of mussels in contaminated seawater.

A simple example can illustrate the sensitivity of filter feeders to very low concentrations of hydrocarbons in water and the potential problems that can result. Chipman and Galtsoff (1949) have reported that oysters filter 200-300 liters of water/day. Assuming a wet weight of 5 grams and a taste threshold of 50 ppm (μg/gm), a simple computation shows that exposure to as little as 1 ppb hydrocarbons in water for one day can lead to significant contamination:

$$\frac{50\ \mu g}{gm} \cdot \frac{5\ gm}{organism} \cdot \frac{1}{200\ l./day/organism} = 1.25\ ppb/day$$

Organisms contaminated with oil do have some capacity for self-cleaning. (Mackin, 1961; Lee et al., 1972; Blumer and Sass, 1970). Apparently, the longer and heavier is the exposure, the more persistent is the tainting. In short-term experiments, Lee found that the mussel, *Mytilus edulis*, discharged more than 90% of the incorporated hydrocarbons after being placed in clean water. However, Blumer and Sass (1970) report much less self-cleaning in organisms exposed to contaminated sediments over longer time periods.

In summary, tainting is a significant sub-lethal problem. Very low concentrations in water (1-10 ppb) are of importance and can lead to tainting of organisms in very short time periods.

Effects of coating.--This section is intended to deal exclusively with the problems associated with coating by a film of oil. This is only of importance when the oil has been weathered, so that the more toxic (at the cellular level) fractions have evaporated. If the toxic fractions are present, the damage done by coating is insignificant compared to the damage done at the cellular level by the low boiling aromatic oil fractions. Most of the data dealing with oil coating discusses the damage done by an oil slick that had weathered at sea for several days before coming ashore (for example, see Chan, 1972).

The organisms most endangered by coating are those which are not able to leave the area where weathered oil is emulsified in the water column, or has settled on the bottom. This immediately excludes from further discussion finfish and other mobile pelagic organisms which can recognize the presence of oil at low concentrations in seawater and presumably avoid higher concentrations. Birds and marine mammals present a different problem since they may not recognize an oil slick until coating is inevitable.

The distinction between the physical effects of a coat of oil on an organism and the effects of the hydrocarbon components of the oil on the physiology of the organism must be repeated here. Toxicity refers to the effects of one or more hydrocarbon fractions which disrupt the cellular or subcellular functions of the organism, so as to cause death if the disruption is widespread and severe enough. This implies that hydrocarbons come into contact with the cell membrane, and either pass within the cell to disrupt metabolic processes, or disrupt the function of the membrane itself. Coating causes disruption of the system or organism level. For example, a coat of weathered oil covering the respiratory apparatus of an organism will not harm individual cells by contact, but will kill the organism by depriving all its cells of oxygen. Death in this case is not a function of the coating agent being a hydrocarbon mixture (weathered oil has lost most of the fractions which are harmful at the cellular level); the same effect could probably be induced by using the same volume of Elmer's glue.

In terms of respiration and feeding interference when considering littoral or benthic organisms, a division can be made by differentiating between sessile and mobile organisms. Whether or not an organism can move away from oil deposited on the bottom plays a large role in determining whether it survives or not. Even if an organism is sessile and becomes covered with oil, it still may be able to protect itself (e.g. bivalves) until the oil is removed or until the oil layer becomes shallow enough for the organism to break through to clean water. (Remember, the cellular toxicities of the hydrocarbons present in the layer are assumed insignificant.) Chan (1972) found that mussels could poke through a weathered oil slick that coated them after the San Francisco spill with only a 3% mortality.

In many filter-feeding organisms, the feeding and respiratory organs are closely coupled, so that interference with one will almost inevitably affect the other. Good examples of these organisms are most molluscs (bivalves, some types of small shrimp, etc.). Many shellfish filter water through their gills and strain out everything, surround the suspended material they do not want with mucus and eject it, eating the rest. At the same time, they receive oxygen from the water passing over the gills. If oil is emulsified in the water, the droplets will be strained out also. As long as the amount of oil is small (a few percent of the total water volume being filtered) the organism should be able to surround the oil in mucus and eject it. A heavier emulsion will probably suffocate the organism. Also, the amount of dissolved oxygen per unit volume in the water fraction of the emulsion may decrease as the amount of oil increases because the oil may be oxidized naturally at a slow rate, using up dissolved oxygen. This could cause suffocation also. It is quite difficult to quantify the amount and composition of oil, length of exposure, extent of emulsification and amount of dissolved oxygen present to obtain an estimate of the susceptibility of organisms to coating. Also, it is difficult to generalize for even small taxonomic groups of organisms, since very wide ranges in response to oil are sometimes found among organisms even within the same genus (the level of classification just above the species).

Movement and attachment to a substrate are also influenced by the presence of a coat of oil, but these are discussed in the section on habitat changes.

If coated for a prolonged period, macrophytic algae ("seaweeds") may show a decrease in photosynthesis due to decrease in incident light penetration and a lack of CO_2. Oil droplets may adsorb on the surfaces of phytoplankton, but because of the short cell division times of most single-celled phytoplankton the population is not likely to be affected. Again, these effects are difficult to quantify.

Zooplankton, which are capable only of small-scale active movement (they can move over long distances by drifting with oceanic currents), may be subjected to oil-water emulsions in a manner similar to that encountered by benthic organisms. Most zooplankton are crustaceans, but many have filter-feeding mechanisms similar to those of bivalves (see Yonge, 1928, for a good summary of the many types of feeding mechanisms employed by invertebrates). This would make these organisms susceptible to coating by an oil-water emulsion. Plankton are commonly found in the surface layers of coastal waters. Because the oil-water emulsion is formed by wind and wave action at the surface, filter-feeding plankton may be subjected to more concentrated emulsions than would be expected in deeper waters. The literature on coating of plankton by oil is sparse and is summarized in a review by Nelson-Smith (1970).

Straughan (1971) investigated the effects of the Santa Barbara spill on several species of marine mammals which inhabit the area, but could come to no conclusions. These mammals must periodically surface in order to receive air, and thus are in danger of being coated with oil. One dead dolphin found washed ashore in Santa Barbara reportedly had its blowhole plugged with oil, although this finding has been disputed (Straughan, 1971).

Many weaned elephant seal pups were coated with oil and were apparently not harmed, although immediate mortality could have been much higher had the oil spill taken place at a time when the pups were feeding. Odell (in Straughan, 1971) reported a tripling in the number of premature births of sea lions, which, like the sea elephants, have rookeries on the islands in the Santa Barbara Channel.

It seems probable that marine mammal mortalities can only be indirectly related to coating. Warm blooded marine organisms must maintain their body temperatures at a higher level than the surrounding water. This requires an efficient insulating layer surrounding the body. Birds use a layer of waterproofed feathers, while mammals usually combine layers of fat with a thick coat of fur as insulation. A coat of oil can significantly change the insulating properties of the fur, perhaps causing the animal to lose heat and lower its resistance to disease. This is just one of several possible hypotheses that can be used to indirectly connect oil coating with marine mammal mortality, although based on current evidence, none of these hypotheses can be accepted conclusively.

Birds are also warm-blooded and thus must insulate themselves against their surroundings. Marine birds have an additional problem because their insulation must also be waterproof. Straughan (1971) summarizes the effects of coating of birds with oil. Aerial species rarely come into contact with oil, whether floating or beached, and thus are not especially endangered. Swimming species are continually subject to contact with floating oil slicks. Often their first reaction upon coming in contact with the oil is to dive beneath it, invariably resurfacing in it, compounding the problem. The oil causes the insulating layer of feathers to mat down, causing the animal to freeze, or die of a disease caused by loss of metabolic heat. The buoyancy maintained by the air-filled feathers is also disturbed. Feeding may become difficult, both because the bird may experience difficulty in movement, and because food sources may be contaminated by oil (Nelson-Smith, 1970).

Habitat changes induced by spilled oil.--One major problem connected with oil activity is the incorporation of oil into sediments. The amount of crude oil and the percentage of different fractions which compose it in the sediments are functions of: (a) the particle size distribution of the sediments, (b) the strength of vertical mixing, (c) the water depth, (d) the time after the spill and the extent of its weathering. The amount of vertical mixing and water depth determine whether or not the oil will reach the bottom by means of forces. Vertical mixing is dependent on the surface winds, the extent of stratification, and current mixing. Also, the density of the oil in the slick is a function of the extent of weathering, because lighter components are lost, making the oil more dense as time progresses.

Once mixed in the water column, oil is usually adsorbed onto the surfaces of any particles suspended in it, generally settling to the bottom after a time. The amount of oil adsorbed by the sediments correlates with particle surface area. On a unit mass basis, it is known that the smaller the sediment particles are, the more total surface area there is. Thus, all other things being equal, there will be more oil in clay sediments than in sandy sediments.

Once incorporated in the sediments, the oil tends to degrade slowly. At the surface of the sediments, aerobic (oxygen utilizing) bacteria can degrade some fractions of the oil, but beneath the aerobic layer, anaerobic (oxygen-free) conditions frequently prevail, which do not allow microbial degradation. Oil in this state is frequently present for months or years before it breaks down, assuming no new oil is introduced in the meantime.

As discussed earlier, the size of the sediment particles plays a major role in determining which organisms live in the sediments. Obviously, the presence of oil will have some effect. Detritus feeders such as many gastropods tend to live in finer sediments (silt and clay). These animals swallow the sediment whole and digest any bacteria and organic matter, excreting the remainder. Filter feeders inhabit coarser sediments (sand and gravel). For detritus feeders, oil in the sediments presents an obvious danger. Absorption of hydrocarbons through the digestive tract is serious, as is the possible destruction of food sources by the oil.

Another problem caused by oil may be either a retardation or acceleration of natural sediment drift rates, which determine the stability of the substratum. This is especially important in coastal areas, where estuaries could silt in, or salt marshes could erode away, their stabilizing grasses having been destroyed.

Summary.--In the preceding sections the biological effects of oil on individual organisms have been reviewed. Several important considerations are apparent from this review:

1) Although direct quantitative comparison of much of the data summarized in Tables II.4.7 to II.4.14 is virtually impossible due to differences in experimental procedures and documentation, a definite qualitative consistency is observed. Most importantly, as other authors have noted, the aromatic fractions of oil pose the most serious environmental problems. Among the most supportive pieces of data leading to this conclusion are: Wilber's comparison of the effects of benzene, n-hexane and toluene on kelp (Table II.4.7); the data for various dispersants reported by Sprague and Carson in Table II.4.8; the experiments on gastropods reported by Ottway (Table II.4.11); and the recent results reported by Lee (Table II.4.12) for the effects of various hydrocarbons on mussels. In each of these cases and all others where some information on the type of compounds causing toxicity is available, the lower boiling, more soluble aromatic fractions are consistently implicated as the primary cause of mortality. This result is consistent with our knowledge concerning the biochemical activity of these highly toxic solvents as compared to that of the higher molecular weight saturated compounds. Although low molecular weight paraffins can cause narcosis, the concentrations required to induce such responses

are extremely high and would not occur from an oil spill. Certain heterocyclic compounds are also known to be quite toxic. However, given the concentration with which these compounds occur in petroleum and their much lower solubilities, it is extremely unlikely that these poisons are the culprit. Thus, henceforth we will focus on the soluble aromatic fraction.

2) On the basis of somewhat fragmentary evidence, it appears that the great bulk of the aromatic fractions will be depleted from within the slick within four days, less under higher wind speeds. Comparison of volatilities and solubilities indicates that very roughly one-half of these compounds will evaporate and one-half will dissolve into the water column.

3) Concentrations of water-soluble aromatic derivatives (aromatic and naphtheno-aromatics) as low as .1 ppm may be toxic to certain marine larvae.

4) Most adult marine organisms are sensitive to soluble aromatic derivatives in concentrations of 1 ppm and lethal toxicity typically occurs at concentrations of 10-100 ppm. In general, crustaceans and burrowing animals are most sensitive, fish and bivalves moderately sensitive and gastropods and flora least sensitive. However, fish and other mobile organisms are generally known to avoid and escape contaminated areas.

5) Chemical communications play an important role in the behavioral patterns of many marine organisms. The full implications of disruption of these communication patterns remain uncertain, as does the exact mechanism of disruption.

However, concentrations of soluble aromatic derivatives in the range of 10-100 ppb may cause significant problems.

6) The incorporation of hydrocarbons in the tissue of marine organisms is primarily of interest due to public health. The individual organisms are apparently not affected. Whether or not cancer can be induced in humans from injestion of carcinogens accumulated in seafood is as yet unknown. However, the potential seriousness of the problem implies that careful consideration be given to these issues. The actual mechanisms of build-up in the food chain also remain uncertain. There is some evidence that incorporation results primarily from uptake directly from sea water and not from ingestion of contaminated food sources. In addition, there is a general, slow degradation of hydrocarbons, indicating that the ultimate fate (after many years) may be stable, innocuous compounds.

7) The development of objectionable taste in seafood (10-50 ppm in the organism) can result from very low ambient concentrations in water (1-10 ppb) of hydrocarbons in a relatively short amount of time (one to a few days). If the contamination in the water is short-lived and concentrations in water are not too high, self-cleaning of the organism may be 90% complete. However, the maintenance of undesirable conditions over longer time periods can result in essentially permanent contamination.

8) The effects of weathered oil result from coating, usually in the intertidal zone, both organisms and substrate. If coating is heavy, the effects may be essentially permanent, due to

smothering of individuals or alteration of substrate textures. Light coating of weathered oil is not, in general, a major problem. Frequency of coating is also important and areas subject to chronic discharge may accumulate the oil, leading to longer-term problems.

The conclusions outlined above provide the basis for assessing the possible impacts of various hypothetical events relating to oil development in the Gulf of Maine. Spill probabilities and trajectories can be used to estimate various hydrocarbon concentrations that can be expected. With this information the impacts on specific organisms can be estimated. The ultimate impact, however, is the effect on communities and the whole ecosystem. These assessments are best made in the context of specific locations and events and are therefore considered in Chapter II.5.

References

Adlard, E.R., "A Review of the Methods for the Identification of Persistent Hydrocarbon Pollutants on Seas and Beaches", J. Institute of Pet., Vol. 58, No. 560, March 1972

Allen, H., 1971, "Effects of Petroleum Fractions on the Early Development of a Sea Urchin", Marine Poll. Bull., 2 (9): 138

Alyakrinskaya, I.O., Experimental Data on The Oxygen Consumption of Sea Water Contaminated by Petroleum; V.M. Biological Station, Novorossiysk, Rostov State Univ., July 11, 1964

Bell, D.L., 1971, The Toxicity and Biological Effects of Oil Pollution. Memo to Environmental Protection Agency, Office of Water Programs, Washington, D.C.

Bellamy, D.J., et al., 1967, "Effects of Pollution from the Torrey Canyon on Littoral & Sublittoral Ecosystems", Nature, 216: 1170

Berridge, S.A. et al., 1968, "The Properties of Persistent Oils at Sea", J. Inst. of Petr., 54 (539), 300-309

Bestougeff, M.A., 1967, in Nagy, Bartholomew and Colombo, Fundamental Aspects of Petroleum Geochemistry, Elsevier Publishing Co., New York

Bigelow, H.B., 1924, Plankton of the Offshore Waters of the Gulf of Maine; Dept. of Commerce, Bureau of Fisheries Document No. 968, Part II

Bigelow, H.B., 1927, Physical Oceanography of the Gulf of Maine, Bulletin of the U.S. Bureau of Fisheries, 40, Part 2: 511-1027

Bigelow, H.B. and Schroeder, William C., 1953, Fishes of the Gulf of Maine, Fishery Bulletin of the Fish & Wildlife Service, Vol. 53, U.S. Government Printing Office, Washington, D.C.

Blumer, M., 1971, "Scientific Aspects of the Oil Spill Problem", Environmental Affairs, 1(1): 54

Blumer, M., 1972, "Submarine Seeps: Are They a Major Source of Open Ocean Oil Pollution?" Science, 176: 1257-1258

Blumer, M., M. Ehrhardt and J. H. Jones, 1972, "The Environmental Fate of Stranded Crude Oil", presented at U.S. Navy Oil Pollution Conf., Washington, D.C., May 2-5, 1972

Blumer, M. et al., 1970, The West Falmouth Oil Spill. Woods Hole Oceanographic Institution, WHOI-70-44, unpublished manuscript, Woods Hole, Mass.

Blumer, M. and J. Sass, 1972, The West Falmouth Oil Spill II. Chemistry, WHOI-72-19, unpublished manuscript, Woods Hole Oceanographic Institute, Woods Hole, Mass.

Blumer, M. and J. Sass, 1972, "Oil Pollution: Persistence and Degradation of Spilled Fuel Oil", Science, 176:1120

Blumer, M. and J. Sass, 1972, "Indigenous and Petroleum-derived Hydrocarbons in a Polluted Sediment", Mar. Poll. Bull., 3, (6): 92

Blumer, M., G. Souza and J. Sass, 1970, "Hydrocarbon Pollution of Edible Shellfish by an Oil Spill", Marine Biology, 5(3): 195

Boylan, D.B., and B.W. Tripp, 1971, "Determination of Hydrocarbons in Seawater Extracts of Crude Oil and Crude Oil Fractions", Nature, 230: 44

Bridie, A.L. and J. Bos, 1971, "Biological Degradation of Mineral Oil in Sea Water", J. Inst. Pet., 57 (557): 270-277

Brower, W.A., D.D. Sisk and R.G. Quayle, 1972, Environmental Guide for Seven U.S. Ports and Harbor Approaches, Nat'l Oceanic and Atmospheric Administration, Nat'l Climatic Center, Asheville, N.C.

Brown, L.R. and R. G. Tischer, 1969, The Decomposition of Petroleum Products in our Natural Waters, Water Res. Inst., Miss. State Univ., State College, Miss.

Bumpus, D.F. and L.M. Lauzier, 1967, Surface Circulation on the Continental Shelf off Eastern North America between New Foundland and Florida, American Geophysical Society, New York

Burns, Kathryn A., Teal, John M., 1971, Hydrocarbon Incorporation Into The Salt Marsh Ecosystem From The West Falmouth Oil Spill, Reference No. 70-69, unpublished manuscript, Woods Hole Oceanographic Institution, Woods Hole, Mass.

Carthy, J.D. and D.R. Arthur, 1968, The Biological Effects of Oil Pollution on Littoral Communities, Institute of Petroleum, London

Castenholtz, R.W., 1967, in Olson, T.A. and Burgess, F.J. (ed.), Pollution and Marine Ecology, Wiley and Sons, N.Y.

Cerame-vivas, M.J., undated, "Biological Consequences of Oil Spills on Marine Life", Department of Marine Science, University of Puerto Rico, Mayaguez, Puerto Rico

Chan, G., 1972, The Effects of the San Francisco Oil Spill on Marine Life, College of Marin, Kentfield, Calif., January 1972

Chipman, W.A., and P.S. Galtsoff, 1949, Effects of Oil Mixed With Carbonized Sand on Aquatic Animals, Special Scientific Report--Fisheries, No. 1, Fish & Wildlife Service, Washington, D.C.

Clark, R.C. and M.Blumer, 1967, "Distribution of n-Paraffins in Marine Organisms and Sediment", Lim. & Ocean., 12: 79

Colton, J.B., 1955, Spring and Summer Distribution of Haddock on Georges Bank; Special Scientific Report--Fisheries No. 156

Colton, B., 1964, History of Oceanography in the Offshore Waters of the Gulf of Maine, U.S. Fish & Wildlife Service, Special Scientific Report--Fisheries No. 496, Washington, D.C.

Colton, J.B. et al., 1968, Physical, Chemical and Biological Observations of the Gulf of Maine, Nova Scotia to Long Island, 1964-1969, U.S. Fish and Wildlife Service, Data Report No. 23

Conover, R.J., 1972, "Some Relations Between Zooplankton and Bunker C Oil in Chedabucto Bay Following the Wreck of the Tanker ARrow", J. Fish. Res. Bd. Can., 28: 1327-1330

Constantinides, and Arich, 1967, in Nagy, Bartholomew and Colombo, Fundamental Aspects of Petroleum Geochemistry, Elsevier Publishing Co., N.Y.

Corner, E.D.S., A.J. Southward and E.C. Southward, 1968, "Toxicity of Oil-Spill Removers ('Detergents") To Marine Life: An Assessment Using The Intertidal Barnacle Elminius Modestus", Mar. Bio., 48: 29

Cowell, E.B., 1969, "The Effects of Oil Pollution on Salt-march Communities in Pembrokenshire and Cornwall", The Jour. of Appl. Ecology, 6(2): 133

Cowell, E.B. (ed.), 1971, The Ecological Effects of Oil Pollution on Littoral Communities, Institute of Petroleum, London

Crapp, G., 1971, in Cowell, E.B. (ed.), 1971, The Ecological Effects of Oil Pollution on Littoral Communities, Institute of Petroleum, London

Cronin, E.L., 1971, Preliminary Analysis of the Ecological Aspects of Deep Port Creation and Supership Operation, Report to U.S. Army Engineers, Alexandria, Va. by Natural Resources Institute, Univ. of Maryland. Nat'l. Tech. Info. Serv., Dept. of Commerce, Springfield, Va.

Dalby, D.H., 1969, "Some Observations on Oil Pollution of Salt Marshes in Milford Haven", Biological Conservation, 1(4): 295-296

Davis, C.C., 1970, "The Effects of Pollutants on the Reproduction of Marine Organisms", FAO Tech. Conf. on Marine Pollution and It's Effects on Living Resources and Fishing, Rome, Italy

Dean, R.A., 1968, "The Chemistry of Crude Oils in Relation to Their Spillage on the Sea", in Carthy, J.D. and Arthur, D.R. (editors), The Biological Effects of Oil Pollution on Littoral Communities, Supplement to Vol. 2, Field Studies, Field Studies Council, London, England

Farrington, J.W. and J.G. Quinn, 1972, "Petroleum Hydrocarbons in Narragansett Bay, Part 1: Survey of Hydrocarbons in Sediments and Clams", Woods Hole Oceanographic Institution, Contribution No. 2880

Farrington, J.W. and J.G. Quinn, 1972, "Petroleum Hydrocarbons and Fatty Acids in Sewage Effluents", in press, JWPCF

Fay, J.A., 1971, "Physical Processes in the Spread of Oil on a Water Surface", in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C.

Floodgate, M.C., 1972, "Microbial Degradation of Oil", Mar. Poll. Bull., 3:41-43

Forrester, W.D., 1971, "Distribution of Suspended Oil Particles Following the Grounding of the Tanker Arrow", J. Mar. Res., 29(2): 151-170

Foster, M., A.C. Charters and M. Neushel, 1971, "The Santa Barbara Oil Spill Part 1: Initial Quantities and Distribution of Pollutant Crude Oil", Environ. Poll., 2:97

George, J.D., 1970, "Sub-lethal Effects on Living Organisms", Mar. Poll. Bull., pp. 107-109.

George, M., 1961, "Oil Pollution of Marine Organisms", Nature, 4808: 1209

Gerarde, H.W., 1960, Toxicology & Biochemistry of Aromatic Hydrocarbons, Elsevier Publishing, London

Goldacre, R.J., 1968, in Carthy, J.D. and Arthur, D.R. (ed.), The Biological Effects of Oil Pollution on Littoral Communities, supplement to Volume 2 of Field Studies, Field Studies Council, London

Gordon, D.C. and P.A. Michalik, 1971, "Concentration of Bunker C Fuel Oil in the Waters of Chedabucto Bay", J. Fish. Res. Bd. of Can., 28(12)

Gould, H.R., Background Paper on Oil & Gas, prepared for Coastal Zone Workshop, Woods Hole Oceanographic Institution, Woods Hole, Mass., May 22-June 3, 1972

Graham, J.J., 1970, "Coastal Currents of the Western Gulf of Maine", ICNAF Research Bulletin, n. 7: 19-31

Graham, J.J., 1972, "Retention of Larval Herring Within The Sheepscot Estuary of Maine", Fish. Bull., 70(2): 299

Graham, J.J., S. B. Chenoweth and C. W. Davis, 1972, Abundance, Distribution, Movements, and Lengths of Larval Herring Along the Western Coast of the Gulf of Maine", Fish. Bull., 70(2): 307

Griffith, D. de G., 1970, "Toxicity of Crude Oil and Detergents to Two Species of Edible Molluscs Under Artificial Tidal Conditions", FAO Technical Conference on Marine Pollution, Rome, Italy

Hartung, R. and G. W. Klinger, 1968, "Fisheries and Wildlife Sedimentation of Floating Oils", papers of the Mich. Acad. Sci., Arts and Letters, Vol. LIII: 23-27

Hasler, H.D., 1970, in Sondheimer, E. and J.B. Simeone, (ed.) Chemical Ecology, Academic Press

Hepple, P., 1971, Water Pollution by Oil, Institute of Petroleum, London

Hoult, D.P., 1969, Oil on the Sea. Proceedings of a symposium on scientific and engineering aspects of oil pollution on the sea, sponsored by MIT and Woods Hole Ocean. Inst., Cambridge, Mass.

Ichiye, T., 1972, "Hydrodynamic Problems Concerning Oil Spillage in the Ocean", Prelim. draft, not for publication. Dept. of Oceanography, Texas A&M.

James, W., 1972, Supertanker Environmental Study: Galveston-Freeport, Texas Region. Texas A&M Report

James, , 1925, Report of the United States Bureau of Fisheries: Preliminary Investigation on Effect of Oil Pollution on Marine Pelagic Eggs, April 1925

Johnston, R., 1970, "The Decomposition of Crude Oil Residues in Sand Columns", J. Mar. Biol. Ass. U.K., 50: 925-937

Kanter, R., D. Straughn and W. Jessee, 1971, "Effects of Exposure to Oil on Mytilus Califoinus From Different Localities", in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C.

Kauss, P.B., T.C. Hutchinson and M. Griffiths, 1972, "Field and Laboratory Studies of the Effects of Crude Oil Spills on Photoplankton", in Proceedings, 18th Annual Technical Conference, Environmental Progress in Science and Education

Kinney, P.J., D.K. Button and D.M. Schell, 1969, "Kinetics of Dissipation and Biodegradation of Crude Oil in Alaska's Cook Inlet", in Proceedings Joint Conference of Prevention and Control of Oil Spills, American Petroleum Institute and Federal Water Pollution Control Administration, December 15-17, 1969, New York, N.Y.

Kuhnhold, W.W., 1970, The Influence of Crude Oils on Fish Fry, FAO Conference, Rome, Italy

LaRoche, G., R. Eisler and C. M. Tarzwell, 1970, "Bioassay Procedures for Oil and Oil Dispersant Toxicity Evaluation", JWPCF, 42(11): 1982

Lee, R.F., R. Sauerheber, and A.A. Benson, 1972, "Petroleum Hydrocarbons: Uptake and Discharge by the Marine Mussel Mytilus edulis", Science, 177: 344

Levy, E.M., 1970, "The Identification of Petroleum Products in the Marine Environment by absorption Spectrophotometry", Wat. Res., 46: 57-69

Levy, E.M., 1971, "The Presence of Petroleum Residues Off the East of Nova Scotia, In the Gulf of St. Lawrence and the St. Lawrence River", Wat. Res., 5: 723-733

Levy, E.M., 1972, "Evidence for the Recovery of the Waters Off the East Coast of Nova Scotia From the Effects of a Major Oil Spill", Wat., Air, and Soil Poll., Jan. 1972

Lewis, J.B., "Effect of Crude Oil and an Oil-Spill Dispersant on Reef Corals", Mar. Poll. Bull., 1972: 59

Little, A.D., Inc., 1969, Machias Bay - Environmental Management, Report to Atlantic World Port, Inc.

Loucks, R.H. and D. J. Lawrence, 1972, "Reconnaissance of an Oil Spill", Mar. Poll. Bull., 1972: 92

Lund, E.J., 1957 "Effect of Bleedwater, "Soluble Fraction' and Crude Oil on the Oyster", Publ. Inst. Mar. Sci., University of Texas, 4: 328-341

Mackin, J.G. and S.H. Hopkins, 1961, "Studies on Oysters in Relation to the Oil Industry", 7, publications of the Institute of Marine Science, U. of Texas

Marak, R.R., Colton, J.B., Foster, D.B., Miller, D., 1962, Distribution of Fish Eggs & Larvae, Temperature, and Salinity in the Georges Bank - Gulf of Maine Area, 1956; Special Scientific Report, Fisheries, No. 412, Washington, D.C., March 1962

Marak, R.R., Colton, J.B., Foster, D.B., 1962, Distribution of Fish Eggs and Larvae, Temperature, and Salinity in the Georges Bank - Gulf of Maine Area 1955; Special Scientific Report--Fisheries No. 411, March 1962

McHarg, I., 1970, Design With Nature, Doubleday/Natural History Press.

McKee, J.E. and Wolf, H.W., 1963, Water Quality Criteria, Calif. State Water Qual. Control Board Publication 3-A

McLeese, D.W., 1969, "Detection of Dissolved Substances by the American Lobster (Homarus americanus) and Olfactory Attraction between Lobsters", Fish. Res. Bd. of Can., 27: 1371

Mills, E.R. and D.D. Culley, Jr., 1972, "Toxicity of Various Offshore Crude Oils to Marine and Estuarine Shrimp", Forestry and Wildlife Management School, Fisheries Section, Louisiana State Univ., Unpublished manuscript.

Mironov, O.G., 1969, "Hydrocarbon Pollution of the Sea and its Influence on Marine Organisms", Helgolander Wiss. Meeresunters, 17, 335-339

Moore, H., 1958, Marine Ecology, Wiley & Sons, Inc.

Moore, S.F., 1972, "A Simple Model for Estimating the Weathering of Oil", a draft, not for publication, M.I.T., Cambridge, Mass.

Morowitz, H.J., 1968, Energy Flow in Biology, Academic Press

Murdoch, W.W., 1971, Environment, Sinauer Assoc.

Murphy, T.A., 1970, "Environmental Effects of Oil Pollution", presented to American Society of Civil Engineers, Boston, Mass., July 13, 1970, EPA, Edison Water Quality Lab., Edison, New Jersey

Nelson-Smith, A., 1968, "The Effects of Oil Pollution and Emulsifier Cleansing on Shore Life in South-West Britain", J. of App. Ecol., 5: 97

Nelson-Smith, A., 1970, "The Problem of Oil Pollution of the Sea", Adv. Mar. Res. 8: 215-306

North, W.J. et al., 1964, "Successive Biological Changes Observed in a Marine Cove Exposed to a Large Spillage of Mineral Oil", Comm. int. Explor. Sci., Mer. Medit., Symp. Pollut. Mar. par Micoorgan. Prod. petrol., Monaco

Odum, E.P., 1971, Fundamentals of Ecology, Sauderes

Ottway, S., 1971, in Cowell, E.B. (ed.) Ecological Effects of Oil Pollution on Littoral Communities, Institute of Petroleum, London

Pacific Northwest Laboratories, 1969, Review of the Santa Barbara Channel Oil Pollution Incident; Battelle Memorial Institute, Richland, Virginia, July 18, 1969

Parker, P.L., J. K. Winters and J. Morgan, Baseline Studies of Pollutants in The Marine Environment, unpublished data presented at the NSF-IDOE Workshop, Brookhaven National Lab., May 24-26, 1972

Paulus, W.C., "Physical Processes of the Marine Environment (Oil Movement Forecasting)", U.S. Naval Oceanographic Office, Washington, D.C.

Perkins, E.J., 1968, in Carthy, J.D. and Arthur, D.R. (eds.), The Biological Effects of Oil Pollution on Littoral Communities, Field Studies Council, London

Phillips, O.M., 1969, The Dynamics of the Upper Ocean, Cambridge Press

Poirier, O.A. and G.A. Thiel, 1941, "Deposition of Free Oil by Sediments Settling in Sea Water", Bull. Am. Ass. Pet. Geol., 25(12): 2170-2180

Portmann, J. E. and P.M. Connor, 1968, "The Toxicity of Several Oil Spill Removers to Some Species of Fish and Shellfish", Mar. Bio., 1: 322

Pritchard, D.W., 1952, "Estuarine Hydrography", Adv. Geophys., I: 243

Rossini, F.D., 1960, "Hydrocarbons in Petroleum", J. of Chem. Ed., 37(11)

Rounsefell, G.A., 1972, "Ecological Effects of Offshore Construction", J. Mar. Sci. Alabama, 2(1): 1-213

Sanders, H.L., Grassle, J.F., Hampson, G.R., 1970, The West Falmouth Oil Spill, I. Biology; WHOI-72-20, unpublished manuscript, Woods Hole Oceanographic Institution, Woods Hole, Mass.

Scarratt, D.J. et al., 1970, "Some Biological and Chemical Investigations of a Major Winter Oil Spill on the Canadian East Coast", Fisheries Research Board of Canada, St. Andrews, New Brunswick, Canada

Shelton, R.G.J., 1971, "Effects of Oil Dispersants on the Marine Environment", Proc. Roy. Soc. of London, 177: 411

Sherman, K. and R.D. Lewis, 1967, "Seasonal Occurrence of Larval Lobsters in Coastal Waters of Central Maine", Proceedings of the National Shellfisheries Association, 57, June 1967

Sidhu, G.S., et al., 1970, "Nature and Effects of Kerosene-Like Taint in Mullet (Mugil cephalus)", FAO Conference, Rome, Italy

Simpson, A.C., 1968, in Carthy, J.D. and Arthur, D.R. (eds.), The Biological Effects of Oil Pollution on Littoral Communities, Field Studies Council, London

Smith, J.E. (ed.), 1968, Torrey Canyon Pollution and Marine Life, Cambridge University Press

Sprague, J.B. and W. G. Carson, 1970, Toxicity Tests with Oil Dispersants in Connection with Oil Spill at Chedabucto Bay, Nova Scotia, Fisheries Research Board of Canada, Tech. Report No. 201

St. Amant, L.S., 1972, "The Petroleum Industry as it Affects Marine and Estuarine Ecology", J. Pet. Tech., April 1972, pp. 385-392

St. Amant, L.S., undated, "Biological Effects of Petroleum Exploration & Production in Coastal Louisiana", Louisiana Wild Life & Fisheries Commission

St. Amant, L.S., 1971, "Impacts of Oil on the Gulf Coast", Tr. of N.A. Wild. and Nat. Res. Conf., Wildlife Management Institute, Washington, D.C.

Strahler, A.N., 1966, A Geologist's View of Cape Cod, Natural History Press, Garden City, N.J.

Straughan, D., 1971, Biological and Oceanographical Survey of the Santa Barbara Channel Oil Spill, 1969-70. Vol. I: Biology and Bacteriology; Vol. II: Physical Chemical and Geological Studies, Allan Hancock Foundation, University of Southern California

Straughan, D., 1972, "Factors Causing Environmental Changes After an Oil Spill", J. Petr. Tech., March, 1972, 250-254

Suess, M.J., 1970, "Presence of Polynuclear Aromatic Hydrocarbons in Coastal Waters and the Possible Health Consequences", Rev. Intern. Ocean. Med., Tome XVIII-XIX

Tagatz, M.E., 19 , "Reduced Oxygen Tolerance and Toxicity of Petroleum Products to Juvenile American Shad", Ches. Sci., 2: 65

Tarzwell, C.M., 1971, in Hepple, P. (ed.), Water Pollution by Oil, Institute of Petroleum, London

Texas Instuments, Inc., 1971, Biological Assessment of Diesel Spill in the Vicinity of Anacortes, Washington, Final Report for EPA, Washington, D.C.

Todd, J.H., J. Atema and D.B. Boylon, 1972, "Chemical Communication in the Sea", MTS Journ., 6(4): 54

Todd, J. H. et al., 1972, An Introduction to Environmental Ethology, WHOI-72-43, unpublished manuscript, Woods Hole Oceanographic Institute, Woods Hole, Mass.

U. of California, Santa Barbara, Calif., 1970, Santa Barbara Oil Pollution, 1969, A Study of the Biological Effects of the Oil Spill Which Occurred at Santa Barbara, Calif. in 1969; Federal Water Quality Administration, Dept. of the Interior

U. of California, Santa Barbara, Calif., 1971, Santa Barbara Oil Spill: Short-Term Analysis of Macoplankton and Fish; Office of Water Quality Research, Environmental Protection Agency

Whittle, K.J. and Blumer, M., 1970, in Hood, D.W. (ed.), Organic Matter in Natural Waters, Institute of Marine Science, University of Alaska

Wigley, R.L., 1956, Food Habits of Georges Bank Haddock; Special Scientific Report--Fisheries, No. 165, Washington, D.C.

Wigley, R.L., 1961, "Bottom Sediments of Georges Bank", J. Sed. Pet., 31(2): 165

Wilber, C.G., 1968, Biological Aspects of Water Pollution

Wilder, O.G., 1970, The Tainting of Lobster Meat by Bunker C Oil Alone or in Combination with the Dispersant Corexit, Fish. Res. Bd. Canada, Manuscript Report Series No. 1087

Wilson, K.W., 1970, "The Toxicity of Oil-Spill Dispersants to the Embryos and Larvae of Some Marine Fish", FAO Conference, Rome, Italy

Zitko, V. and W.V. Carson, 1970, The Characterization of Petroleum Oils and their Determination in the Aquatic Environment, Fisheries Research Board of Canada, Tech. Report No. 217

Zobell, C.E., 1971, "Sources and Biodegradation of Carcinogenic Hydrocarbons", in Prevention and Control of Oil Spills, American Petroleum Institute, Washington, D.C.

Zobell, C.E., 1964, "The Occurrence, Effects, and Fate of Oil Polluting the Sea", Adv. in Wat. Poll. Res., Academic Press

Chapter II.5
Estimates of Specific Biological Impacts of Spills and Discharges

II.5.1 Introduction

In this chapter, we will attempt to address directly the likely biological impacts associated with specific hypothetical spills and discharges. In so doing, it would have been desirable if our knowledge was of the sort which could have been formulated into a quantitative model of the ecological relationship within the Georges Bank and coastal communities,which model could have been exercized and explored in the same manner as the economic simulations of Volume I. Unfortunately, both time and data constraints have prevented the development of such a model. Thus, our estimates in this chapter will be of a strictly qualitative nature. Further and more importantly, we are going to allow our intuitive judgement, developed by an intensive literature search, conversations with marine biologists from England to the Gulf, several months' direct contact with the Woods Hole community, and direct observation of a number of oil spills, a little more rein in this chapter than in the others. Thus, the conclusions in this chapter are somewhat more speculative and perhaps more sensitive to our biases than in the others. Nonetheless, considerable information has been amassed on oil pollution and we feel that one can make rather strong statements in certain areas.

II.5.2 The large Georges Bank spill

The biological effects of a single oil spill are dependent upon the location and amount of spillage, the composition of the oil, especially with respect to aromatic fractions, and the particular assemblage of organisms in the region of the spill. Due to weathering processes, which reduce the lower boiling fractions (boiling point < 220°C-250°C) to a fraction of a percent of their original amount in 48-96 hours, the effects of the spill can also be expected to change significantly during the first 48-96 hours after spillage. In particular, direct effects related to the soluble, generally lower boiling point fractions are therefore exhibited during this initial time period following the spill, but are not a problem over longer time periods unless dispersion of the soluble fractions is prevented, for example by incorporation in sediments, or the discharge is continuous as in the case of discharges from the oil-water separators. In short, for a large offshore spill in relatively deep water, we feel that the first two to four days will be critical.

Consider a very large, million gallon spill released in summer. Summer is probably the worst season biologically because the spill has a higher average time on Georges Bank and the biota are most active during this time of year. Chapter II.2 indicates that such a spill will spread to about three square miles in about 12 hours and about 10 square miles in 4 days. The spill will be moved around the Bank at a mean speed over one knot relative to the bottom and about .3 knots relative to the water below the wind-induced boundary layer in wiggly, roughly elliptical orbits. Chapter I.6 indicates that only a small fraction, in the neighborhood of 1%, of the larvae of even those species with relatively concentrated spawning periods and grounds would rise into the spill. In the approximately 4 days in which toxic responses predominate, the track of such a spill would cover about 400 sq miles or 3% of the total Bank area. The actual area traversed would be less than this because cyclic tidal excursions would bring the spill over the same area twice or thrice.

Even assuming the spill kills all the eggs and larvae which rise into it, the total amount of larvae affected is quite unlikely to be large enough to noticeably affect succeeding generations of adult species. Virtually all of the threatened organisms are members of populations which have reproductive characteristics ("r strategists") adapted to sudden environmental changes such as may occur in the surface waters of the open ocean. In addition, most species are very small (microscopic to barely visible) and reproduce for periods of 100 days or more, creating very high replacement rates for any individuals that are killed, whether by predation by fish, oil spills or other causes. There is no evidence that there will be any significant toxic impact on adult finfish, and considerable evidence to the contrary.

After the soluble fractions have been reduced to non-toxic concentrations, the slick may still produce some biological effects, either by direct coating of organisms floating on the surface, or from incorporation of hydrocarbons by injestion of oil droplets dispersed in the water column. The responses could occur throughout the time the slick remains on the Bank, which during the summer would average about 10 days, or a total track of 1,000 sq miles, which is about 10% of the Bank area. Some phytoplankton and zooplankton may become coated during this latter period, but most of these organisms do not occur at the immediate surface of the water. Filter feeding, pelagic crustaceans injest oil droplets, but apparently excrete the unwanted material unchanged (Conover, 1971).

Oil spills originating on Georges Bank will require a minimum of 30 days to reach land (Cape Cod) (see Chapter II.2). After that time, the spill will have weathered to such an extent that only floating globs, dispersed over an area much greater than the original spill, will remain. Chapter II.2 estimates that between 0 and 5% of these spills will hit the coast. They will probably have little biological impact due to the relatively low toxicity of this tarry residue. Some biological impact will undoubtedly be occasioned by attempts to clean the tar balls up.

It appears quite possible that concentrations of the order of ppb of oil would reach the bottom from a spill in the shallower portions of the Bank, and as much as 10 ppb in the extremely shallow (5-10 fathom) areas. Unless the Georges Bank crude contained an unusually high percentage of aromatics, such concentrations are quite unlikely to be toxic to the bottom dwellers. Sublethal effects on behavior are considerably more likely although almost nothing is known about the Georges Bank bottom dwellers in this regard. The conditions would be relatively short-lived and the sublethal effects presumably transitory although we have no real data.

Incorporation of hydrocarbons and tainting of shellfish will also occur at these concentrations. Once again the exposure will be short-lived enough so that the organisms will cleanse themselves from a taste point of view. However, certain hydrocarbons, including some carcinogens, will be retained indefinitely. The public health significance of this accumulation is an open question.

II.5.3 Chronic spills and discharges offshore

Chapter II.1 estimates from Coast Guard data that a very large find operated to 1971 Gulf Coast standards would, on the average, generate 1,000 spills per year at peak production, which spill would average about 100 gallons each for a total average volume per year of 108,000 gallons. Such a find would be produced from approximately 20 platforms, indicating that each platform would on the average suffer one small spill per week, or an average of about 10 gallons per day. Since this average is made up of a large number of spills considerably smaller than 100 gallons and a very small number of spills a great deal larger, the typical week will see much less than this amount spilled.

However, these spills need not concern us here, for the biological impacts resulting from the chronic, small spill will be overwhelmed for certain hypothetical developments by two types of discharge:

1) the oil in the water discharged from the oil-water separator if large amounts of water are produced from the reservoir;

2) the oil in the ballast water discharge from tankers loading offshore for those hypotheses employing tankers for transport to shore.

Chapter I.6, under the assumption that one barrel of water is produced for every three barrels of oil (approximately the Gulf average), which water is separated to present OCS standards (50 ppm), estimated that a very large-volume production platform could discharge 125 gallons of oil per day in a continuous fashion along with the water. Not only is this quantity considerably larger than the average spillage due to small spills, but also it is quite likely that the oil remaining in the water after separation will contain a higher fraction of aromatics than the crude, for the gravity separation process is ineffective against dissolved matter.

Chapter I.6 uses a two-dimensional dispersion model to obtain estimates of the area within which concentrations exceeding a specified amount will be found. Under unrealistically worst-case assumptions (1 ft mixing depth and 3 ft^3/sec diffusion coefficient,) the 100 ppb contour encloses 10 sq miles and the 1 ppm .0004 sq miles. Even if all the oil were soluble aromatics, toxic effects would be limited to the most sensitive phytoplankton and this effect would be localized in a very small portion of the Bank. Under still severe but much more likely assumptions with respect to percent aromatics (10% of oil), mixing depth (3 ft), dispersion coefficient (10 ft^3/sec), the area in excess of 100 ppb aromatics decreases to a circle whose radius is about 40 ft. In short, it is extremely difficult to envision the impact of the oil-water separator being noticeable at the population level. However, these calculations do show that some local water quality degradation can take place and should be observed carefully.

Sub-lethal effects could occur in a wider-ranging area. However, even from an individual organism point of view it is difficult to identify the situation as critical. For the case of one-foot mixing depth, which produces the largest area of contamination due to vertical movement, most organisms would move in and out of the contaminated area irregularly. Most individuals would not be subject to continuous exposure to the soluble hydrocarbons.

The continuous discharge problem does not appear to be a serious threat. No adverse effects of separator discharge have been noted in the Gulf as yet and it is established fact that the area under the platforms supports unusually dense populations. However, the margin of safety may not be as great as sometimes assumed. At the very least, research into the fractional composition of separator discharge is indicated.

Some of our hypothetical developments employed tanker transport to shore. For these options, tankers will arrive at our offshore loading terminal on the Georges Bank at 40 to 70% ballast, depending on weather conditions. This ballast water will have to be discharged. Under present operating procedures, this ballast water will contain at least 100 ppm oil. At 50% ballast and 100 ppm, the oil discharge for a very large field would average 2,100 gallons per day. While this is by far the single largest discharge associated with an offshore development, it may not be the most biologically damaging. This will depend largely on the amount of soluble aromatics in this oil, which in turn will depend on the amount which the oil has weathered in the two-way transit. There appears to be no data on the fractional composition of ballast water oil.

There is little point in attempting to separate this oil on the tankers, since vessel movement makes gravity separation below 100 ppm almost completely ineffective. Further, there may be little point in transferring the oil to a platform and separating it. The operation will be rather expensive and gravity separation is ineffective against the biologically active dissolved fractions. If this oil does contain appreciable amounts of soluble aromatics, segregated ballast tanks may be required.* This will add about 15% to the initial cost of the tanker transport system.

Finally, with respect to tanker transport of offshore oil, it is important to note that Phillips reports that the

---

*Alternatively, a flexible membrane approach being developed by M.I.T. for segregating oil and ballast may prove feasible.

tanker-mooring buoy system is the principle source of oil spill problems at their Ekofisk operation. This was verified by on-site discussions with the operating personnel. However, no quantitative data is available. Almost none of the Gulf platforms use vessel transport to shore. Therefore, our estimates of offshore spill incidence from tankers based on ordinary tanker service may be optimistic for the option of tanker transport of a Georges Bank discovery.

II.5.4 Non-petroleum drilling and production effluents

In addition to oil, offshore drilling and production activity can generate a number of other effluents. These include produced water from the reservoir, already mentioned, well drilling fluids, more commonly referred to as drilling mud, and drill bit cuttings, as well as small volumes of certain additives.

Drilling mud is a mixture of clay and water, supplemented with inert weight materials and selected additives. During drilling, this mixture is continuously circulated from the surface mud pit, down the drill string, through the drill bit, up the annulus formed by the drill string and the wall of the drill hole, and back to the mud pit. After a residence time in the mud pit, the mud is recirculated until it is either chemically soured by the formation or so laden with fine-grained cuttings that handling is prohibitive. The mud is then discharged over the side and new mud made up from the raw materials. The drilling mud serves to remove the cuttings from the hole, to prevent formation fluids from entering the hole, to seal the formation through the deposition of an impermeable wall cake, and to lubricate the drill string. The basic clay-water mixture partially performs all of these tasks. However, the primary function of the mixture is to form a gel medium capable of suspending and transporting the cuttings to the surface. Bentonite, an inert sodium montmorillinite clay, is commonly used. The weight material acts to increase the hydrostatic pressure exerted by the mud column at the bottom of the hole so that highly pressured oil and gas cannot enter the hole, causing a blowout. Barite, an inert barium sulfate, is the most commonly used weight material. The selected additives are chosen for their direct effect on the formation or for their indirect effect on the clay-water gel medium. Examples of direct effect additives are cotton seed, which acts to seal the formation, and diesel oil, which acts to lubricate the drill string, thereby increasing bit life. Examples of indirect effect additives are ferrochrome lignosulfonate, carboxylmethylcellulose (CMC), and sodium hydroxide, which aid in limiting the effects of formation chemical contamination and temperature on the gel strength and fluid loss (sealing) characteristics of the gel medium. In addition to this relatively common drilling mud, literally hundreds of special purpose muds have been developed to attack specific reservoir problems. However, from a pollution point of view, the above materials constitute almost all the effluent. To determine the volumes of effluent discharge which one might expect on Georges Bank, we must reference our discussion to typical well as shown in Figure I.2.6. In this case, 13-5/8 inch casing is set to 3,000 feet. An additional 9,000 feet of 9-5/8 inch casing is set to 12,000 feet. The volume of the hole is approximately 1,355 barrels. Adding an additional 600 barrels in the mud pit, the total mud in the system must be at least 1,955 barrels. Depending on the formation pressures encountered during the drilling of the well, the mud could range from 9.45 pounds per gallon (ppg) to 17.60 ppg. The higher mud weights might be required to prevent potential blowouts from highly pressured formations. The higher weights are obtained by increasing the proportion of barite. Thus, the total weight of drilling mud which could be discharged would be a maximum of 1,000,000 pounds per well. Of this amount, as much as 13,500 pounds could be ferrochrome lignosulfonate. Some 6,750 pounds could be sodium hydroxide. An additional 82 barrels of diesel fuel might be added as a lubricant. The barite and bentonite would amount to some 676,000 pounds. Based on the sodium hydroxide content of the fluid, the approximate pH is 10.

The amount of usage obtained from the mud depends on the formations encountered. However, discussion with industry sources indicates it would be reasonable to assume that the volume of mud discharged per well is approximately equal to the volume of the hole. At present, mud is disposed of over the side, with the exception of mud containing diesel oil, which apparently is taken ashore. USGS regulations require a hydrocarbon content of less then 50 ppm in any mud discharged offshore.

Under the assumption that the entire mud system is dumped once per well and assuming a worst case of 200 wells drilled over two years in a field of 25 sq mi, we obtain the following effluent levels.

Drilling bit cuttings*	257,000,000 pounds
Bentonite & barite	135,200,000 pounds
Sodium hydroxide	1,350,000 pounds
Ferrochrome lignosulfate	2,700,000 pounds

Considering simply the burial effect of the clay, barite and cuttings, this amounts to a coverage of 0.006 feet over the area of the field. Because of the importance of substrate texture on biological activity, there is cause for concern from such deposition. The most serious problem is in the coarse, gravelly substrates, where the benthic biomass is highest and there are many filter feeders (crustaceans and bivalves). However, the amount shown above can be at most locally significant.

Actually, some of the discharge will never settle on the bottom. Caustic soda (sodium hydroxide) and barium sulfate are common constituents of sea water and would be quickly and easily dispersed in the marine environment. Potential effects on pH by sodium hydroxide are prevented by mixing with sea water before discharge to adjust the pH of the effluent to approximately 8, which is typical for ocean waters. Barium sulfate is not known to have any undesirable effects on marine organisms. Typical normal concentrations in sea water are near 50 milligrams per cubic meter (mg/m^3) (Harvey, 1967). The solubility, however, is near 100 mg/m^3, indicating that much of the barium sulfate would go into solution.

Ferrochrome lignin sulfonate is an organo-metallic compound related to tannic acid. It is commonly found in waste discharges from paper pulp mills. Little is known

*Assumes sandstone of specific gravity of 2.7.

about its possible toxic effects. Mackin and Hopkins (1961) have reported that tannic acid has no apparent toxic effect on oysters. This is insufficient data to draw conclusions about the possible effects of lignin sulfonate. However, it is very unlikely that its toxicity (if any) would be more damaging than the effects of soluble hydrocarbons in the oil-water separator discharge. Future work on the toxicity and other biological effects of this drilling mud additive is warranted.

The discharge of drilling muds can be expected to discolor the water and increase its turbidity on a very localized basis. Such changes in water quality could have some detrimental effect on plankton caught in the discharge plume. Phytoplankton activity would be reduced due to attenuation of light inputs. Filter feeding zooplankton may be disrupted due to unfamiliarly high concentrations of suspended sediments. Fish and other mobile organisms would be expected to simply avoid such contaminated areas. Due to the very localized nature of these discharges there is virtually no expectation of any impact on populations and higher levels of organization.

After the oil well has been drilled, the well must be completed. Production casing is set and some wells are plugged and abandoned. This requires cement operations in the offshore field. The principle additives for cement operations are accelerators (calcium chloride, sodium chloride, sodium silicate), retarders (calcium lignosulfonates, lignins, carboxymethyl-hydroxyethylcellulose acetic acid, tannin), dispersants (alkyl aryl sulfonates, polyphosphates, lactones, gluconates), and special additives (acrylic copolymers, paraformaldehyde sodium chromate). Reliable estimates of potential discharges are not available. However, these discharges are extremely small in total volume.

Following the completion of the wells, the field is brought into operation. The next set of effluents is associated with the processing of production fluids. The separation of the three-phase mixture of gas, oil and water requires the employment of glycol to prevent hydrate formation in the gas lines, amines to scrub the sulfur dioxide from the gas stream, and emulsion breakers to separate water from the mixed stream. The gas separator materials which usually become saturated with petroleum liquids are taken to shore for treatment. Emulsion breakers used in offshore oil/water separation are ethoxalated high molecular weight materials such as fatty acids from palm oils, coconut oils, or long chain hydrocarbon polymers. These fatty acids are primarily oil-soluble materials which are treated with ethylene oxide to make them partially miscible with water. However, their solubility in water is extremely low and accordingly the emulsifier itself stays with the crude oils separated from the mixed stream. Concentrations of use will vary from 10 parts per million to 400 parts per million. Accurate estimates of the quantities to be discharged are unavailable, but they are undoubtedly less than 10 ppb in the discharge water. No data is available on the toxicity of these materials but it is extremely unlikely they could have any effect at these concentrations.

The final source of effluents results from the daily operation and maintenance of the production equipment. Under Geological Survey regulation, all solid waste materials must be incinerated or transported to shore for disposal. All sewage must be incinerated, transported to shore, or otherwise treated so that the effluent shall contain no more than 50 ppm of biochemical oxygen demand, 150 ppm of suspended solids, and a minimum chlorine residual of 1.0 mg/liter after fifteen minutes of retention. There appears to be no biological justification for the regulation against discharging sewage offshore.

II.5.5 The nearshore spill

The coast of New England is sufficiently heterogeneous in terms of biota, landform morphology, and currents to inhibit the application of a description of the effects of oil on a generalized section of coast. A detailed assessment of the vulnerability of a location to spilled oil requires specific data on these factors. For practical purposes, it has been assumed here that the coast is composed of two landform types: the indented rocky coast similar to that found on the eastern coast of Maine, and sandy beaches, similar to those of Cape Cod. The existing conditions on the New England coast are described in Chapter II.4.

The hypothesized spills occurring close to the New England coast can be characterized by two extremes: the extremely large spill of greater than 3 million gallons, and small chronic spill (< 100 gallons/incident) of oil from the terminal or refinery complex. Also, the effect of weathered oil which comes ashore from an oil spill on Georges Bank is assessed.

II.5.5.1 The rocky shoreline

The case of a proposed tanker terminal at Machias Bay, Maine, has been studied in detail (Moore and Dwyer, 1972) and this area is used here as an example of a typical segment of the rocky coasts of New England.

The 3 million gallon oil spill.--Chapter II.2 describes the trajectory of an extremely large oil spill released 1, 2, 4, and 8 miles offshore of an idealized coast of Maine near Machias (a straight line). Hypothetical slicks drift under the influence of various possible currents present in these waters, and predictions of the probability of the slick touching shore are made. This analysis examines only the gross drift of the slick, ignoring the case of a nearshore spill where transport of oil within estuaries and embayments is much more probable. In harbors or bays having peak tidal currents, the major portion of the transport process will be by tidal current alone, and the spill trajectory analysis of Chapter II.2 is incapable of accounting for tidal movements.

Qualitatively, an extrapolation from the recent "Tamano" spill in Casco Bay, Maine can be made: any spill whose final area is within a factor of 10 to 100 of the area of the bay in which the spill occurs poses a very real threat to all the beaches in the bay. Although this is a rather sweeping generalization based on qualitative speculations it is highly reasonable in light of the large tidal currents and excursions which occur in the Machias Bay region.

Potentially toxic concentrations of the soluble fractions of oil may accumulate in restricted waters, and may kill or taint a wide variety of organisms (Chapter II.4, Section 5). The potential damage of a spill depends largely upon the time between spill release and shore impact. Due to weathering processes, the soluble fractions (boiling point < 220°C-250°C), which are the most toxic, are decreased rapidly, and within 48-96 hours are probably reduced to a fraction of a percent of their original amount.

Probably the worst spill case conceivable biologically is the release of a 3 million gallon spill in the mouth of Machias Bay at low slack tide. It is safe to expect that virtually the entire shoreline of Machias Bay would be coated by oil within 24-48 hours. Such an event would have extreme biological consequences. Intertidal zones would be heavily coated with fresh oil, which could be expected to contain sufficient soluble aromatic components to expose all organisms to concentrations well in excess of 100 ppm. As a result, most species of nearshore organisms would be threatened with lethally toxic concentrations (see Tables II.4.5-10). The most serious damage would probably occur in mud flats and other unconsolidated sediments found far up in embayments. The heavy oil coating could lead to semipermanent changes in substrates, preventing recovery of damaged areas, especially the recovery of commercially important species such as soft-shell clams, bloodworms, and sandworms. The potential damage to the small salt marshes of the coast would also be quite extensive.

Many of the organism populations which are subjected to high concentrations of dissolved hydrocarbons in an embayment could be completely wiped out. Furthermore, the presence of weathered oil in sediment and on rocks (which may remain for months or years after a spill) may inhibit the immigration of organisms of the same species, which would have repopulated the area. Also, many organisms not killed outright would be expected to ingest significant concentrations of hydrocarbons, causing tainting of edible species, especially shellfish.

In addition to damage to the shores of Machias Bay itself, significant amounts of oil would be expected to come ashore outside Machias Bay, most likely along the coast to the southwest (Chapter II.2). The biological damage of oilings outside of Machias Bay (still assuming a spill point at the mouth of the bay) would be expected to be less extensive. The oil would be more extensively weathered, and the slick would be more dispersed, since it had been floating for a long period. The season of the year and the distance of the spill from shore will also greatly affect the spatial and temporal distribution of the oil slick coming ashore. In general, the longer a slick takes to get to shore, the less biologically damaging are its consequences.

Small spills.--Chapter II.1 estimates that the mean number of spills in the vicinity of a refinery at Machiasport serving all of New England's non-residual oil consumption in 1978 at 4% growth rate will be about 160, of which 100 is the mean of the tanker barge spills, 37 refinery and 24 storage. The mean amount spilled per spill is estimated at about 1,000 gallons; however, the typical spill will be much smaller. These estimates are based on a reasonably pessimistic set of assumptions. For example, if the refinery is operated according to Milford Haven experience, the estimated number of spills drops to about 40 and the mean amount spilled per spill to 200 gallons. In any event, the near-terminal environment will be stressed at irregular intervals of a few days by small spills. A single spill in this size range will produce a slick with an area of a few acres. In terms of hydrocarbons dissolved in the water column, an individual spill of this size is insignificant. If the spill point is close to shore, and if the spill is not controlled artificially (booms, etc.), some of the oil may wash ashore. Although the length of shoreline hit with a single chronic spill slick is obviously much less than that contacted by a large spill, the recovery time for the biotic community on the shore will be much shorter. Thus, permanent changes in the biota in the immediate vicinity of the terminal are almost inevitable. Some deterioration of marshes and flats within the range of tidal excursions at the terminal is possible. However, Milford Haven, an almost completely enclosed estuary with a very large tidal range (20'), still supports shellfishing as well as 400,000 barrels/day of refining. These beds have had to be closed from time to time but no long-run accumulation of hydrocarbons has been proved (Baker, 1972).* It appears there is a very significant difference with regards to the impact of chronic, small spills between a well-run and a casually-run terminal.

---

*Baker has examined Milford Haven sediments over time by drying and solvent extraction. This method could easily miss hydrocarbon buildup and changes which would be revealed by more sophisticated techniques.

II.5.5.2 Sandy shoreline

The extremely large spill, if it comes ashore, will almost certainly be more damaging to sandy shorelines than to rocky shorelines, due to the wider variety and abundance of animals found in areas with unconsolidated sediments (Chapter II.4, Sections 3 and 5). Salt marshes are frequently found behind sand bar beaches. Their vulnerability to the physical (abrasion) and chemical (toxicity) effects of oil slicks is documented by Baker (in Cowell, 1971). As with other habitats, it was found that salt marshes are susceptible to repeated oil coatings, if there was insufficient recovery time between the spills.

Intertidal sediment deposits (mud flats, beaches, etc.) are much more common than along rocky coasts. The organisms found in these sediments are typically quite sensitive to the toxic and sublethal effects of hydrocarbons, as well as to the incorporation of oil in the sediments, which changes the nature of the substrate in addition to coating the organisms present.

II.5.6 Refinery discharges

Some of the hypothetical developments simulated in Volume I involved a single, very large regional refinery of approximately one and a half million barrels per day capacity in 1978 serving the region's entire non-residual oil consumption. Two locations for this refinery were hypothesized: deepwater Maine and southeastern New England. Chapter II.1 finds that the spill hazard presented by the refinery itself is small compared to the spill hazards generated by the ships serving this refinery. Therefore, in this section we will concentrate on the planned discharges into the water which would emanate from such a refinery.

In order to obtain some idea of the effluents which would be generated by such a refinery, discharge permit applications prepared by 18 U.S. refineries to comply with amendments of the Rivers and Harbors Act were obtained from the Corps of Engineers. This data source has some obvious shortcomings: (1) it is the refineries reporting on themselves; (2) some of the permit application forms are not filled out or internally inconsistent, as close perusal of the data below will reveal. In part this may be the fault of ambiguities in the Corps instructions. Nonetheless, it is the best data we were able to obtain, and in general is somewhat more conservative and complete than data contained in industry periodicals. The refineries in this sample are shown in Table II.5.1. They cover a wide range of size and age.

A key variable in refinery discharges is water usage. In general it is cheaper to reduce the water used than to treat it. Figure II.5.1 indicates the wide range of water usage in the sample. The industry feels that it is possible to get down to about 25 gallons of water per barrel of oil processed. Notice that some of the newer refineries in areas where water is expensive approach this figure. Refineries with low water usage consume (feedwater makeup,

Table II.5.1

Refinery	Size (bpd)	Age	Water Intake 1000's of gpd	Water Discharged 1000's of	g/bbl
1 Mobil, Riverside, RI	10,000	1925	2,180	2,200	219
2 Gulf, Belle Chasse, LA	160,000	1971	27,170	24,168	169
3 Citgo, Lake Charter, LA	275,000	1943	145,000	237,500	921
4 Humble, Baton Rouge	466,000	1909	90,530	78,000	194
5 Humble, Baytown, TX	360,000	1970	37,000	25,000	94
6 Humble, Benicia, CA	80,000	1968	4,780	4,660	56
7 Amoco, Texas City	220,000	1933	26,500	14,800	120
8 Texaco, Lockport, IL	76,000	1911	27,890	22,600	367
9 Chevron, Perth Amboy	80,000	1950	61,917	60,000	786
10 Humble, Linden, NJ	155,000	1909	202,500	202,000	1,306
11 Hess, Port Reading, NJ	75,000	1958	2,330	1,010	31
12 Arco, Philadelphia	155,000	1950	21,100	16,400	136
13 Getty, Delaware City	140,000	1956	320,000	320,000	2,285
14 Mobil, Paulsboro	90,800	1933	35,280	27,604	389
15 Texaco, Eagle Point, NJ	91,000	1949	8,640	4,650	95
16 Gulf, Philadelphia	168,000	1954	58,086	48,524	345
17 Sun, Marcus Hook, PA	160,000		124,550	124,517	
18 Humble, Bayonne, NJ			23,970	23,970	

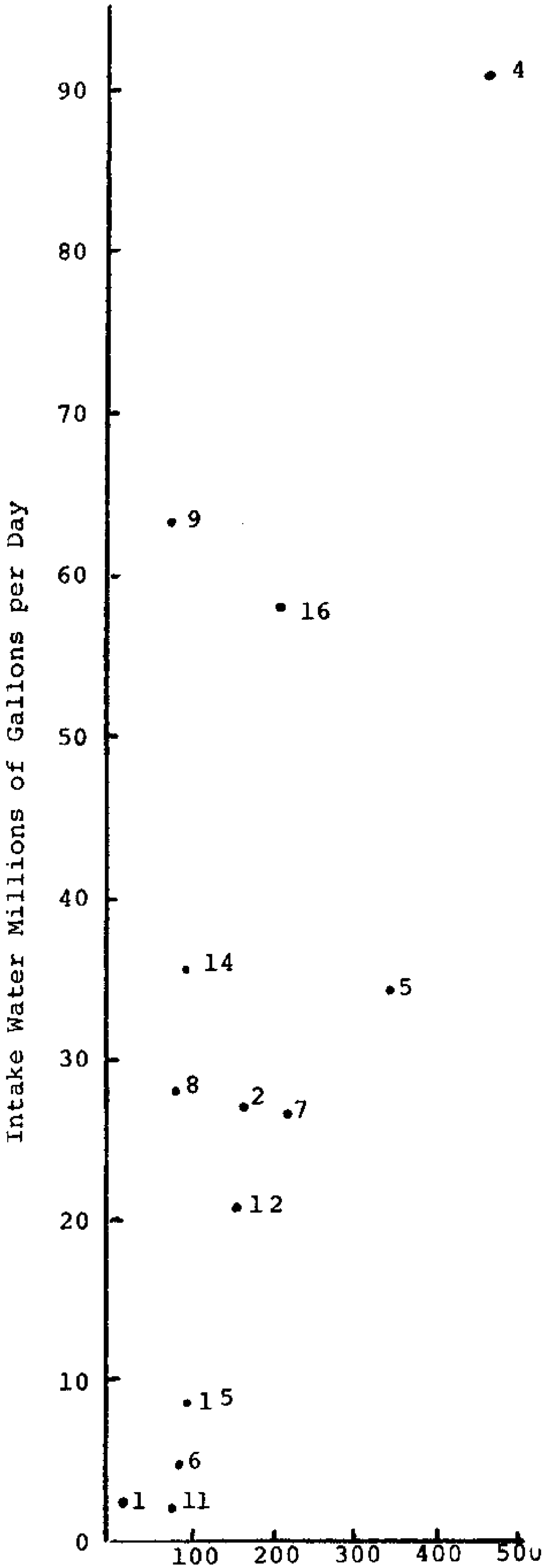
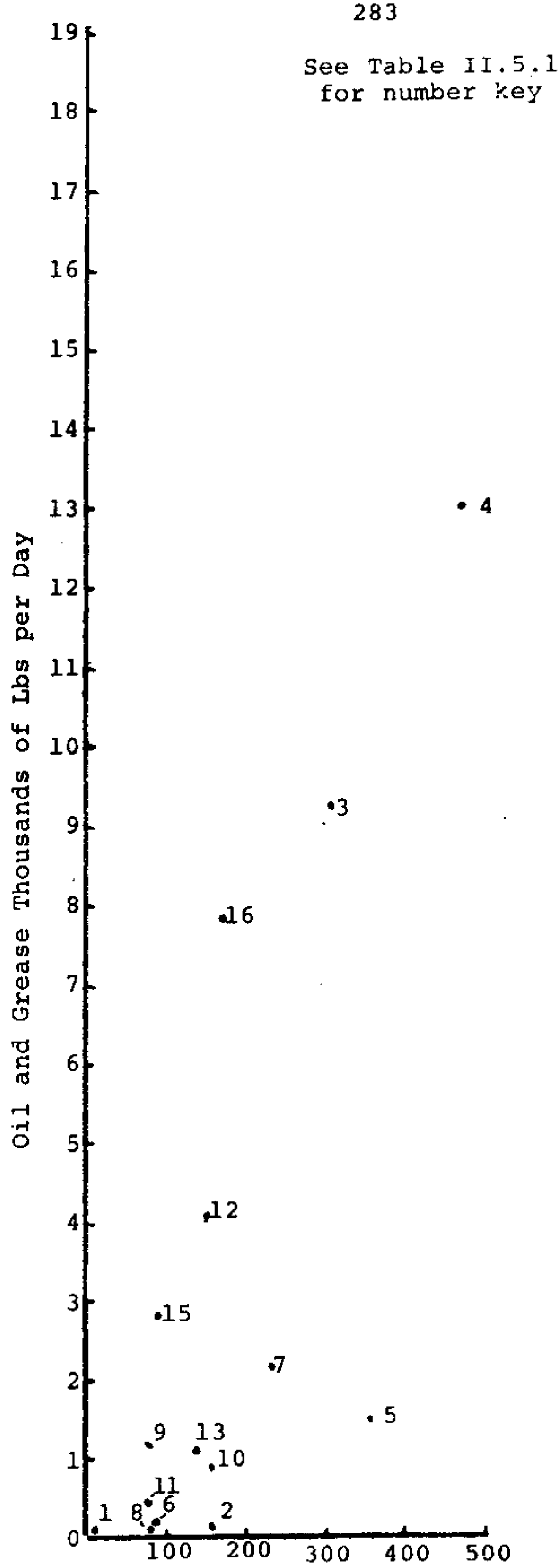


Figure II.5.1



Refinery Size 1000's BPD

Figure II.5.2

evaporation) up to 50% of the water they use. At 25 gallons per barrel, a 1.5 million bpd refinery would require 40 million gallons per day of which about 20 million gallons would be returned. This presents a substantial problem for at least the southeastern New England option. For example, at the Dighton site, the Taunton River has an average flow of 360 million gallons per day which could supply such a refinery. During dry spells, however, the flow frequently drops to approximately 70 million gallons per day which would be hard put to supply 20 million gallons of consumptive use. Ground water is also limited in the area. It appears that any large southeastern New England refinery would have to rely at least part of the time on municipal water as do some of the New York and California refineries.

Figure II.5.2 indicates the hydrocarbon discharges reported by the refineries in the sample under the heading "Oil and Grease". No information on hydrocarbon fractions is given. Once again there is an extremely wide range. The best of the lot, the Humble refinery at Benicia (San Francisco Bay) claims .002 lbs/bbl hydrocarbons which corresponds to 10 ppm in the discharge water. This appears to be an achievable figure.

The Milford Haven refineries, which are rather closely monitored by the South Wales River Authority, operate at less than 30 gallons per barrel and average less than 25 ppm although there are considerable variations in hydrocarbon content from sample to sample (Howells, 1972). The River Authority reports that 50 ppm can result in a sheen on the surface of the estuary. The Cherry Point (Puget Sound) refinery reports maximum oil contents of 15 ppm. Data on fractional composition of this oil is limited. The Humble Baton Rouge refinery, an older refinery in the process of being upgraded, currently employing secondary treatment on some of its wastewater, reports a total oil content which varies between 20 and 50 ppm, of which a minimum of 10% and a maximum of 30-40% is dissolved - the higher values resulting when some piece of equipment malfunctions. The basic problem is that the extensive gravity separation and flocculation employed is almost completely ineffective against that portion of the soluble fraction which has dissolved into the water and most biological processes operate preferentially on paraffins before aromatics. Balancing this is the fact that refineries are especially careful to keep soluble products streams and wastewater streams segregated. Although oil-water solubility is a complex process which is dependent on the non-soluble fractions present, mixing time and mixing energy (McAuliffe, 1969), such contact, if at all extended, could result in dissolved concentrations much higher than the 50 ppm and less discussed above.

Assuming Benicia standards, a 1.5 million bpd refinery would discharge about 300 gallons of oil per day. The discharge of such a volume of oil, especially if it's principly solubles, in riverine or restricted estuarine bodies could have some rather striking consequences. Baker (Cowell, 1971) has observed a salt marsh in Southampton destroyed by refinery discharge combined with tidal action which deposited the surface film on the marsh with each outgoing tide.

Under the worst-case assumption that the bulk of this oil is soluble aromatics, to be reasonably safe from any sort of toxic effects, we shall need concentrations in the neighborhood of 100 ppb or approximately two to three orders of magnitude of dilution if the bulk of this oil is soluble aromatics. This could probably be achieved by a properly positioned, openwater outfall. It is essentially the same problem as that of the continuous discharge from platform oil-water separators addressed in Chapter I.6, except that the volumes are about ten times larger and the concentrations somewhat lower. Assuming enough net transport so that the outfall does not discharge into the same water twice, a mean current of .25 knots and one knot respectively, and the two-dimensional dispersion model of Chapter I.6, concentrations would be below 100 ppb outside a plume whose area under a variety of assumptions concerning mixing depth and diffusion coefficient is given below.

Table II.5.2
Areas Within 100 ppb Contour for 20,000,000 gallon/day Discharge (square n. miles)

Oil Concentration		25 ppm		50 ppm	
Disp. Coeff.	Mix. Depth	.25 knt.	1 knt.	.25 knt.	1 knt.
10 ft^2/sec	3	3	.4	25	3
	10	.08	.04	.7	.08
30 ft^2/sec	3	1	.1	8	1
	10	.03	.01	.2	.03

For likely values of these parameters, it appears that the desired dilution could be accomplished without too much difficulty in open water by a properly positioned outfall. Whether or not one could do it in a semi-enclosed body such as Narragansett or Machias Bay would require some careful analysis. The Milford Haven experience would seem to indicate that it might be done.

A regional refinery served on the products side by tanker/barge would have one other source of oil discharges: the products carriers' ballast. The bulk of the incoming ballast will be transferred to the departing crude carriers, perhaps after skimming. However, occasionally arrival patterns will be such that ballast water is in oversupply, in which case a discharge will result. Also, the water separated from the recovered oil will be discharged. However, the volumes involved are much lower than those discussed above. Bantry Bay claims 5 ppm oil in this water after long-term retention with heating and the oil companies are promising 15 ppm for similar facilities at the Tapline terminus. With proper care and design ballast water transfer does not appear to be nearly as important a problem as refinery wastewater.

The Corps of Engineers data also contains information on oxygen demand, Figure II.5. 3. Once again there is an extremely large range. However, assuming a relatively clean refinery and an outfall designed to obtain the hydrocarbon dilution discussed above, BOD and COD do not appear to be a problem. At Port Reading standards, the discharge water would have an oxygen demand of 100 mg/liter, which after a factor of 1,000 dilution would have no noticeable effects on oxygen levels.

"Total Solids" content in the sample of refineries was much more highly correlated with size than were the other emissions, Figure II.5.4. These solids might produce some localized turbidity and bottom accretion problems in the immediate vicinity of the outfall. On the average, about 20% of these solids were listed as suspended. The rest presumably are dissolved but there are some inconsistencies in some of the permit data.

The water discharged from the sample refineries averages 10-20° higher than ambient in the summer and about 25° higher in the winter. However, some of the newer refineries report almost no differences between wastewater and ambient temperatures, probably due to longer retention times in biological treatment ponds and much more extensive air cooling. In general, a refinery which solves its other environmental problems will not present a significant thermal pollution problem.

The permit data also contains reported discharges of heavy metals which are displayed in Table II.5.3. We have been unable to identify any consistent pattern in this data and it appears likely that some of the reports are not

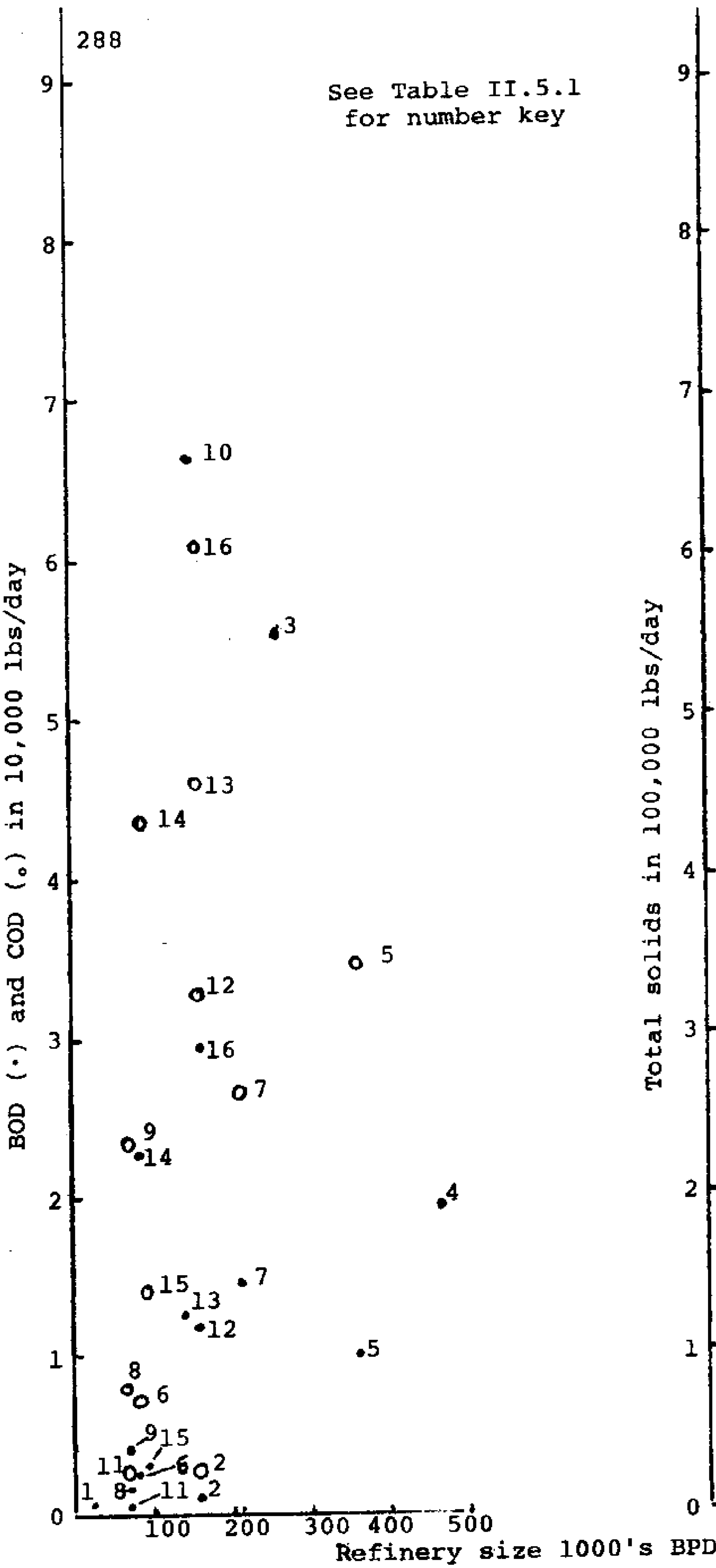


Figure II.5.3

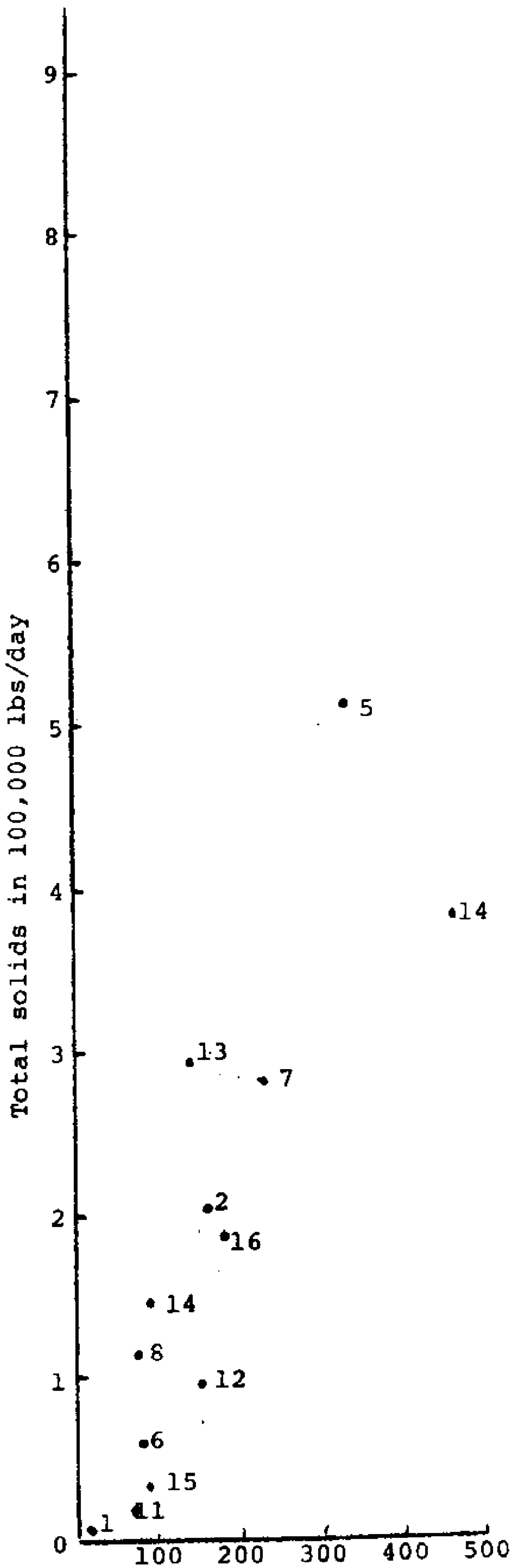


Figure II.5.4

Table II.5.3
Reported Discharges of Selected Heavy Metals
(pounds/day)

		Cr	Co	Cu	Fe	Pb	Hg	Ni
1.	Riverside	.32		.02	.0918			1.65
2.	Belle Chasse	73.0						
3.	Cities Service	59.23		.01	1,445	218	.42	10
4.	Baytown	16	28	4.0	36	23	.2	8.1
5.	Baton Rouge	52			336			
6.	Benicia				110		.1	
7.	American	136		7.4	76	1		7
8.	Lockport	27.54		6.74	76.56	18.94		18.8
9.	Chevron	10.56		16.12	2.98	31.76		14.30
10.	Linden	29	430	120	665	540	2.12	390
11.	Hess	.2		1.05	24.1	.84		.42
12.	Phil. Arco	4.62		3.27	15.25	3.54		2.73
13.	Getty				73	170.3		
14.	Paulsboro	27		42	275			
15.	Eagle Point	62.7		8.3	159	2.75		
16.	Phila. Gulf	155.37		5.91	506.66	48.68		12.49

complete. Very generally, copper runs at concentrations of .02 to .15 parts per million by weight in the discharge water with lead, chromium and nickel about the same. Often refineries which have the higher concentrations of copper have the lower concentrations of chromium, perhaps reflecting differing policies toward the corrosion-inhibitor tradeoff. Iron is considerably higher, with concentrations up to 2.5 ppm. Mercury is present at levels of 1 ppb in some of the reports.

Pringle (1968) reported extreme toxicity of soft-shell clams at .02 ppm copper. Raymont and Shields (1962) reported an LD_{50} of .1 ppm in sea water for the sandworm *Nereis virens*. This worm lives in and digests clay and silt sediments. These sediments are known to adsorb and accumulate metal ions, increasing concentrations by as much as several orders of magnitude. Thus, at least copper is a potential problem, perhaps requiring the same kind of dilution postulated for the hydrocarbons. Some of the other metals, particularly lead, chromium and mercury may also present problems, but we have not investigated these issues.

It should be obvious that before one can make a final judgement about the environmental impact of a regional refinery, some rather detailed analysis is called for. Specifically, a complete preliminary design for the refinery must be developed including wastewater treatment processes and precise outfall location, actual effluent streams including petroleum by fractions estimated and these streams combined with the detailed hydrographic properties of the outfall location to compute effluent plumes under a number of different tidal and runoff conditions. Only at that point will we be in a position to make a reasonably firm assessment of the biological impact of the refinery. At this point, however, it does not appear impossible to reduce this impact to a very localized effect in the immediate vicinity of the outfall. Finally, some of the foregoing may argue for splitting regional refining capacity among a number of separated sites.

References

Baker, J., 1972, Orielton Research Station, Pembroke, England (private communication).

Cowell, E. (ed.), 1971, The Ecological Effects of Oil Pollution on Littoral Communities, Institute of Petroleum, London.

Howells, W. R., 1972, South West Wales River Authority (private communication).

McAuliffe, C., 1969, "Determination of Dissolved Hydrocarbons in Subsurface Brines," Chemical Geology, Vol. 4.

McAuliffe, C., 1966, "Solubility in Water of Paraffin, Cyclo-Paraffin, Olefin, Acetylene, Cyclo-olefin, Chromatic Hydrocarbons," Journal of Phys. Chem., Vol. 70, No. 4.

Mackin, J., and Hopkins, S., 1961, "Studies on Oysters in Relation to the Oil Industry, no. 7," Institute of Marine Science, University of Texas.

Moore, S., and Dwyer, R., 1972, "A Preliminary Assessment of Environmental Vulnerability of Machias Bay, Maine to Oil Supertankers," M.I.T. Parsons Laboratory Report No. 162.

Pringle, B. et al., 1968, "Trace Metal Accumulation by Estuarine Mollusks," Journal of Sanitary Engineering, Vol. 94, No. SA3, Proc. Paper 5970.

Raymont, J., and Shields, J., 1962, "Toxicity of Copper and Chromium in the Marine Environment," Proceedings International Conference on Water Pollution Research, London.

U.S. Department of the Army, Corps of Engineers, Application for Permit to Discharge or Work in Navigable Waters and Their Tributaries (various).

Chapter II.6
The Impact of a Regional Refinery on Air Quality

II.6.1 Introduction

The purpose of this chapter is to make a preliminary estimate of the increase in the region's air pollution which would result from the regional refineries hypothesized earlier. The principle atmospheric pollutants emanating from oil refineries are sulphur oxides, hydrocarbons, nitrogen oxides, and carbon monoxide. Other emissions of less importance include particulates (aluminum silica), aldehydes, ammonia and organic acids.

The key variables in determining the amount of emissions for a standard fuel refinery such as we are analyzing are:

1) the quantity and type (principally sulphur content) of crude processed
2) the type of fuel burned by the refinery
3) facilities for control and prevention of emissions
4) the mix of product output.

The major sources of these effluents are listed in Table II.6.1.

Table II.6.1
Potential Sources of Specific Emissions from Oil Refineries

EMISSION	POTENTIAL SOURCES
Oxides of Sulfur	Boilers, process heaters, catalytic cracking unit regenerators, treating units, H_2S flares, decoking operations.
Hydrocarbons	Loading facilities, turnarounds, sampling, storage tanks, waste water separators, blow-down systems, catalyst regenerators, pumps, valves, blind charging cooling towers, vacuum jets, barometric condensers, air-blowing, high pressure equipment handling volatile hydrocarbons, process heaters, boilers, compressor engines.
Oxides of Nitrogen	Process heaters, boilers, compressor engines, catalyst regenerators, flares.
Particulate Matter	Catalyst regenerators, boilers, process heaters, decoking operations, incinerators.
Aldehydes	Catalyst regenerators.
Ammonia	Catalyst regenerators.
Odors	Treating units (air-blowing, steam-blowing), drains, tank vents, barometric condenser pumps, waste water separators.
Carbon Monoxide	Catalyst regenerators, decoking, compressor engines, incinerators.

II.6.2 Background data

During the late fifties and early sixties, a study known as the "Joint Project" was undertaken to determine the quantity and nature of emissions from oil refineries located in Los Angeles County (reference 1). The results of that study have been the base that gives a quantitative description of the emission produced by oil refineries and have been updated and released by the U.S. Department of Health, Education and Welfare through different publications (references 7-10). A recompilation of this emission data is summarized in Table II.6.2 and will be used later for estimating the emissions of the proposed refinery under study.

Such an estimation will be conservative in that very recent refineries have demonstrated considerably improved performance with respect to atmospheric pollutants.

Table II.8.2 **Emission factors for oil refineries.**

TYPE OF PROCESS	PARTICULATES	SULFUR OXIDES	CARBON MONOXIDE	HYDROCARBONS	NITROGEN OXIDES	ALDEHYDES	AMMONIA
BOILERS AND PROCESS HEATERS							
Lb/1000 bbl oil burned	840	NA	Neg.	140	2,900	25	--
p.p.m. range					50-400[b]		
Lb/1000 c.f. gas burned	0.02	NA	Neg.	0.03	0.23	0.003	--
p.p.m. range					25-200[b]		
FLUID CATALYTIC CRACKING UNITS (FCC)							
Lb/1000 bbl fresh feed	61	525	13,700*	220	4.2[b]	19	54
p.p.m. range		308-2190[a]	0-7.8[a]	98-1213[a]	8-394[a]	3-130[a]	67-675[a]
MOVING-BED CATALYTIC CRACKING UNITS (TCC)							
Lb/1000 bbl fresh feed	17	60	3,800*	87	4.2[b]	12	6
p.p.m. range		65-141[a]	0-4.1[a]	87-1655[a]	7-62[a]	9-177[a]	29-103[a]
FLUID CATALYTIC CRACKING UNITS*							
With electrostatic precipitator as % of catalytic recirculated.	0.0009[a]						
Without electrostatic precipitator as % of catalityc recirculated	0.005[a]						
MOVING BED CATALYTIC CRACKING UNITS*							
High efficiency centrifugal separators as % of catalytic recirculated.	0.002[a]						
COMPRESSOR INTERNAL COMBUSTION ENGINE							
Lb/1000 c.f. gas burned	--	--	Neg.	1.2	0.9	0.1	0.2
BLOWDOWN SYSTEMS							
Lb/1000 bbl refinery capacity							
With control	--	--	--	5	--	--	--
Without control	--	--	--	300	--	--	--
PROCESS DRAIN AND WASTE WATER SEPARATORS							
Lb/1000 bbl waste water							
With control				8			
Without control				210			

TYPE OF PROCESS	PARTICULATES	SULFUR OXIDES	CARBON MONOXIDE	HYDROCARBONS	NITROGEN OXIDES	ALDEHYDES	AMMONIA
VACUUM JETS							
Lb/1000 bbl vacuum destillation							
With control				——			
Without control				130			
COOLING TOWER							
Lb/10^6 gal. cooling water circulated				6			
MISCELLANEOUS LOSSES							
Lb/1000 bbl refinery capacity							
Pipeline valves and flanges				28			
Vessel relief valves				11			
Pump seals				17			
Compresor seals				5			
Others (air blowing, sampling, etc.)				10			
STORAGE TANKS (Lb/day/1000 bbl storage capacity)							
CRUDE OIL							
Vap. press. >1.5 psia. Fixed roof				9.1[a]			
" " " " Float. "				4.8[a]			
" " <1.5 psia Fixed "				4.5[a]			
" " " " Float. "				1.8[a]			
PETROLEUM DISTILLATE							
Vap. press. >1.5 psia. Fixed roof				4.7[a]			
" " " " Float. "				4.8[a]			
" " <1.5 psia Fixed "				1.6[a]			
" " " " Float. "				1.7[a]			
SEALS IN PUMPS AND COMPRESSORS (Lb/day/seal)							
Centrifugal pumps packed seals				4.8[a]			
" " Mech. "				3.2[a]			
Reciprocal " packed "				5.4[a]			
All pumps seals				4.2[a]			
Compressor				8.5[a]			
Valve in liquid service (Lb/day)				0.486[c]			
" " gaseous " "				0.108[c]			
All valves "				0.198[c]			

TYPE OF PROCESS	PARTICULATES	SULFUR OXIDES	CARBON MONOXIDE	HYDROCARBONS	NITROGEN OXIDES	ALDEHYDES	AMMONIA
GASOLINE HANDLING EVAPORATION							
Filling tanks vehicles (Lb/1000 gal. throughput)							
Splash filling				8.2[d]			
Submerge filling				4.9[d]			
LEAKAGE (Valves, pumps, etc.)							
Lb/1000 bbl refinery capacity				60[a]			

* Those emissions are complety controlled when waste heat boilers are used.

a Reference 1

b Reference 9

c Reference 7

d Reference 10

All others values taken from reference 8

II.6.3 Estimation of pollutant levels from regional refineries

In generating our estimates, we will consider two cases with respect to product output:

	All New England	No Resid
Gasoline	28.9 %	45.6%
Kerosene/jet	6.0	6.4
Diesel	13.25	24.0
Distillate #2	13.25	24.0
Residual	38.6	

These situations correspond to the All New England and No Resid options studied earlier in Volume I.

The refinery will not have a high grade of complexity; it will produce no lubricating oils or petrochemicals.

The straight run yield of gasoline is an important parameter that has to be taken into account because it determines the capacity of the cracking units of the refinery which in turn can be an important source of emissions. Two values have been taken for this parameter, 20% and 30% yield of straight run gasoline at 400° B.P. range.

With respect to refinery fuel, two cases were considered: one using .5% sulphur fuel oil and another using natural gas. In the case of natural gas, 2,000 grains of sulphur per million cubic feet was assumed. The sulphur content assumed in the fuel oil assumes that standard 1975 Massachusetts regulations are applied to the refinery.

Finally, we varied the degree of pollutant control. Our less stringent case involves: fluidized bed catalytic units, no waste gas boilers, no special hydrocarbon control on catalytic units or blowdown systems, floating roof tanks without recovery, water cooling. The more stringent case employs moving bed catalytic units, waste gas boilers which effectively eliminate the bulk of the carbon monoxide emissions, recovery and recycling of storage tank evaporation, and 50% air cooling.

In order to present a feeling for what the resulting numbers mean, we have compared them with an estimated amount of pollutants which will result from the end use of the products. In so doing, it was assumed that the sulphur content of the heating fuel and residual will satisfy the different states' regulations of sulphur content, which on the average is 0.79% for 1975. The federal auto emissions regulations for 1975 were also applied. Thus, the resulting percentages are a rough estimate of the overall increase in regional air pollutant levels, under each of the assumed sets of circumstances, if the region refines its own oil.

The results are given in Tables II.6.3 and II.6.4. Inspection of Table II.6.3 reveals that the particulate and sulphur oxide emissions are critically dependent on the fuel the refinery uses. Sulphur is somewhat dependent on the amount of hydrocracking used. Sulphur emission can be cut to very low levels if the refinery fuel is clean enough. Carbon monoxide can be effectively eliminated by reburning. Hydrocarbon emission can be cut by a factor of three by more stringent control but even then will represent an increase of about 10% in the region's unburned hydrocarbon load, if regional refineries process all the region's oil consumption. Industry sources indicate that an old-style refinery will lose about 1-1/2% of its throughput to evaporation; a modern refinery, about 1/2%. Nitrogen oxides represent a relatively difficult control problem, responding only to the type of fuel the refinery uses.

Table II.6.3
Emissions from the Refinery Compared to the Emissions Produced by the Use of the Refinery Products

CASE A:	Gasoline	28.90 %
	Kerosene	6.00 %
	Diesel	13.25 %
	Dest.# 2	13.25 %
	Residual	38.60 %

DESCRIPTION	Part.	SO_x	CO	HC	NO_x
Released by usage of fuel	574	3,588	16,739	2,392	2,747
Released by refinery for:					
FUEL OIL (SRGAS yield 20%)	109	410[b]	Neg[a]	284-689[d,f]	375
	20%	11.4%	Neg	11.9-28.8%	13.6%
FUEL OIL (SRGAS yield 30%)	118	490-419[b,d]	2,100-Neg[e]	249-723[d,f]	376
	20.6%	13.6-11.7%	12.5%-Neg[e]	12.5-30.2%	13.7%
NATURAL GAS (SRGAS yield 20%)	14	0.4[c]	Neg	286-691[d,f]	156
	2.4%	Neg	Neg	11.9-28.9%	5.7%
NATURAL GAS (SRGAS yield 30%)	16	80-110[d]	2,100-Neg[e]	301-725[d,f]	157
	2.8%	2.2-0.3%	12.5%-Neg[e]	12.6-30.3%	5.7%

a Negligible
b Assuming 0.5 % Sulfur fuel
c Assuming 2,000 grains/10^6 s.c.f. of gas
d Depends of the type of catalytic unit
e The lower values are when waste gas boilers are used
f The lower value is for hydrocarbons control on storage tanks, blowdown systems, etc.

All values are in Lb/1000 bbl refinery capacity and in percent

Table II.6.4
Emissions from the Refinery Compared to the Emissions Produced by the Use of the Refinery Products

CASE B: Gasoline 45.6 %
Kerosene 6.4 %
Diesel 24.0 %
Dest.# 2 24.0 %

DESCRIPTION	Part.	SO_x	CO	HC	NO_x
Released by usage of fuel	338	2,655	26,759	3,694	2,812
Released by refinery for:					
FUEL OIL (SRGAS yield 20%)	125	552-426[b,d]	6,000-Neg[a,e]	648-308[d,f]	375
	37%	20.8-16.0%	22.4%-Neg	17.5-8.3%	13.3%
FUEL OIL (SRGAS yield 30%)	135	640-436[b,d]	6,000-Neg[a,e]	786-322[d,f]	376
	40%	24.1-16.4%	22.4%-Neg	21.3-8.7%	13.4%
NATURAL GAS (SRGAS yield 20%)	18	142-16[c,d]	6,000-Neg[a,e]	650-310[d,f]	156
	5.4%	5.3-0.6%	22.4%-Neg	17.6-8.4%	5.5%
NATURAL GAS (SRGAS yield 30%)	21	230-26[c,d]	6,000-Neg[a,e]	788-324[d,f]	157
	6.4%	8.7-1.0%	22.4%-Neg	21.3-8.8%	5.6%

a Negligible
b Assuming 0.5% Sulfur fuel
c Assuming 2,000 grains/10^6 s.c.f. of gas
d Depends of the type of catalytic unit
e The lower values are when waste gas boilers are used
f The lower value is for hydrocarbons control on storage tanks, blowdown systems,

All values are in Lb/1000 bbl refinery capacity and in percent.

II.6.4 Local impact

While the relative increase in overall regional pollutant loads is useful in obtaining a feel for the magnitude of the problem, it has almost nothing to do with the impact of these emissions on the locale surrounding the refinery. This will depend on the meteorological conditions in the precise area, the ambient flora and fauna (including humans), the ambient pollutant load already existing and such controlable variables as refinery stack height. We have not conducted such a study in this report and obviously, such a study should be conducted before any decision as to a regional refinery is made for, from the above, it is clear that even under the best of circumstances, the refinery is going to increase local pollutant loads of certain pollutants several times. However, a few generalities may be in order.

With respect to ground level sulphur concentrations for a given refinery and location, the principle variable is stack height. By making the stack high enough, one can reduce these concentrations to just about any desired level. Figures II.6.1, II.6.2 and II.6.3 indicate maximum ground level sulphur concentration as a function of stack height for a number of wind conditions for a 170,000 barrel per day refinery. In general, each 300,000 barrels per day of refinery capacity is roughly equivalent to a very large (1,000 megawatt) fossil fuel power plant. Thus, a refinery large enough to meet all of New England's requirements would be equivalent to four or five such generating plants from a sulphur point of view.

The principle problems associated with hydrocarbons and nitrogen oxides are smell and smog. Hydrocarbon odors can be detected downstream of a refinery for several miles under the right conditions. The magnitude of smog problem will be critically dependent on the meteorological conditions and ambient pollutant levels in the refinery locale.

Our analyses indicate that a refinery large enough to process all the region's oil consumption will be roughly equivalent to a million-person town as far as smog generation is concerned, with the important difference that a considerable amount of this pollutant load will be released at stack rather than ground levels. In short, the smog problem associated with the refinery should be given careful study before any final decision is made, especially if the refinery location is in a highly populated area.

Finally, the refinery will generate some noise, principally from process furnaces. This has been a source of complaint of neighboring communities on otherwise quiet nights. However, recently, refineries have been built immediately adjacent to residential areas in which property line noise levels were below ambient conditions. Given some care in planning proper buffer zones, the noise problem should be solvable without a large increase in cost.

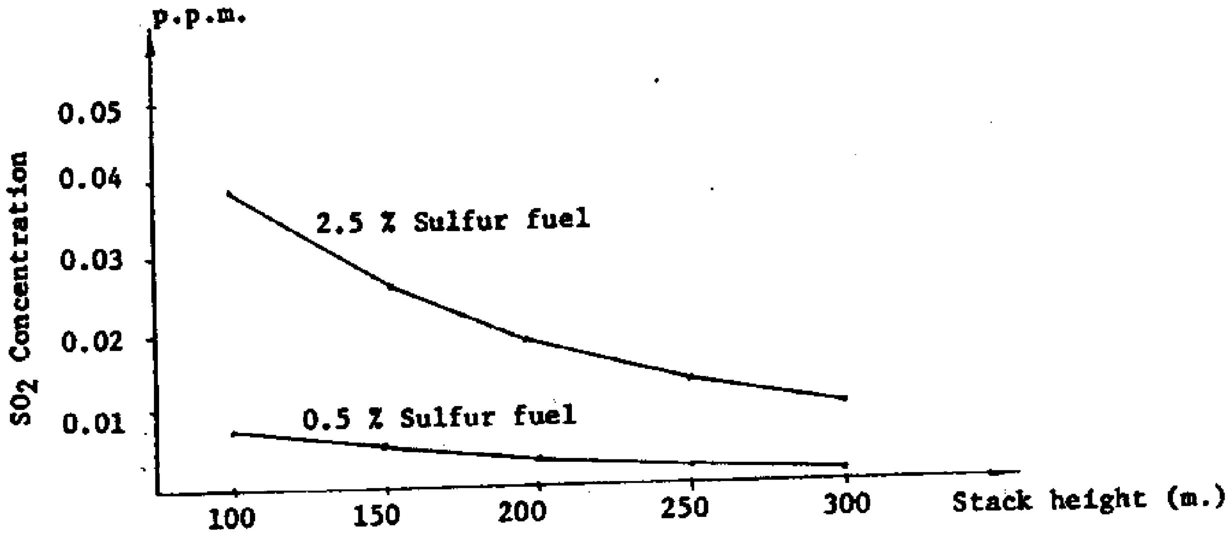


Fig. No. II.6.1 - Hourly maximum ground level concentrations of SO_2 and different stack heights with a wind speed of 6 m/sec. (STABLE ATMOSPHERE)

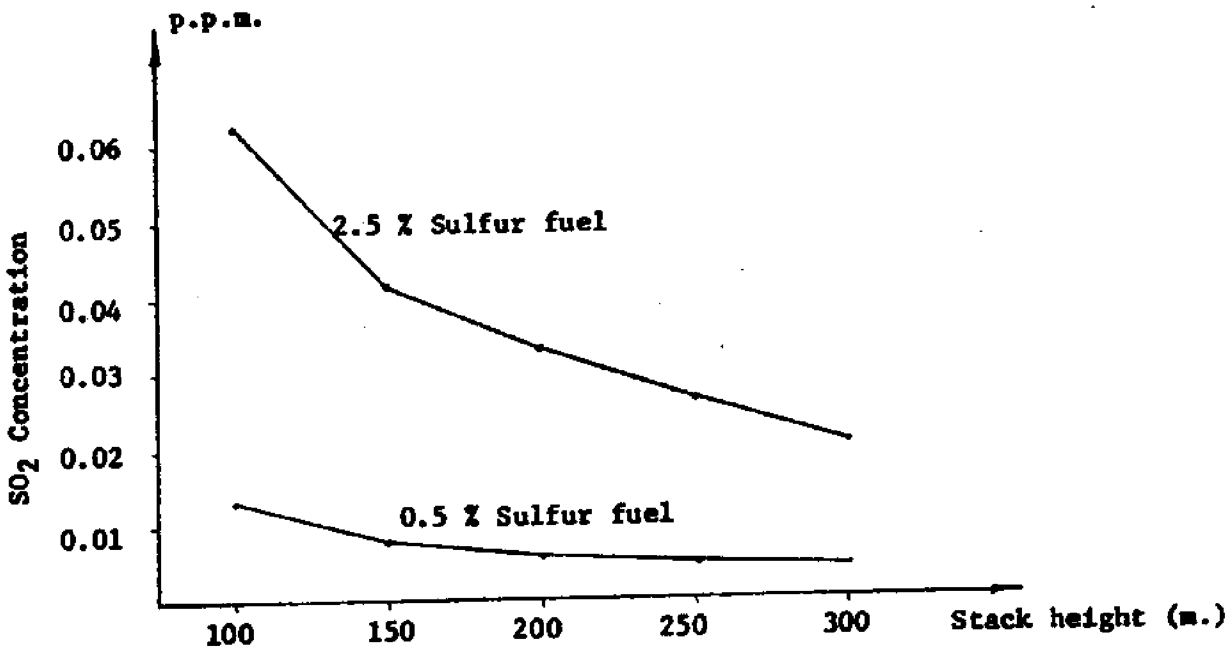


Fig. No. II.6.2 - Hourly maximum ground level concentrations of SO_2 and different stack heights with a wind speed of 2 m/sec. (STABLE ATMOSPHERE)

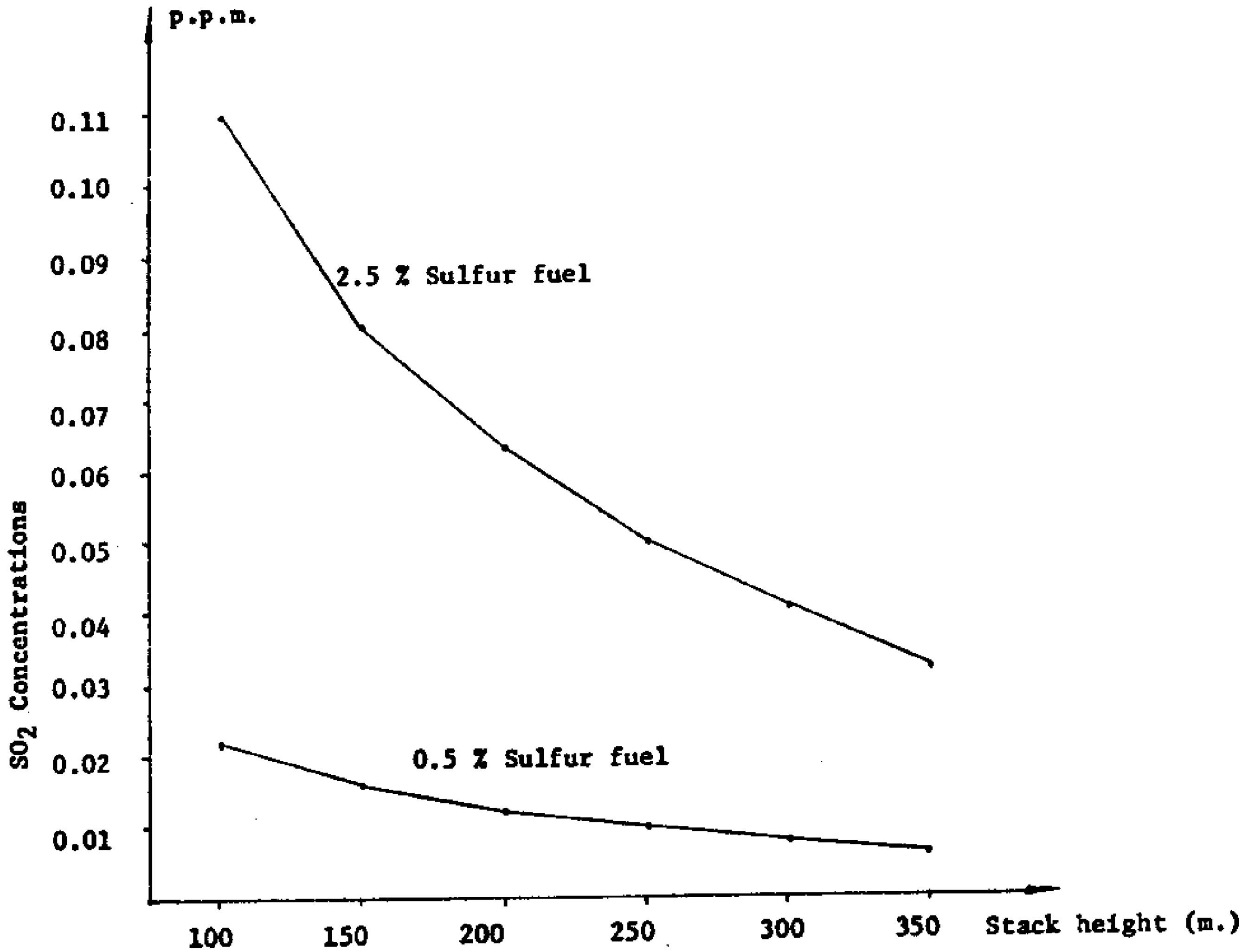


Fig. No. II.6.3 - Hourly maximum ground level concentrations of SO_2 and different stack heights with a wind speed of 10.3 m/sec. (UNSTABLE ATMOSPHERE)

References

1. Atmospheric Emissions from Petroleum Refineries. Public Health Service Publication No. 763 (1960).

2. "Plant Designed to Protect the Environment" - Hydrocarbon Processing - March 1972, p. 115.

3. "Cherry Point Refinery" - The Oil and Gas Journal, January 24, 1972.

4. "How Humble Controls its Environment at Benicia" - The Oil and Gas Journal - March 24, 1969, p. 102.

5. "L.A. Cracker Modified to Cut Emissions" - The Oil and Gas Journal, July 24, 1972, p. 49.

6. "EPA Rules Mean Big Outlay to Refineries" - The Oil and Gas Journal, April 3, 1972, p. 28.

7. Air Pollution Engineering Manual - U.S. Department of Health, Education and Welfare, Public Health Service Publication No. 999-AP-40.

8. "Compilation of Air Pollutant Emission Factors" - U.S. Environmental Protection Agency - Office of Air Programs Publication No. AP-42, February 1972.

9. Control Techniques for Nitrogen Oxide Emissions from Stationary Sources - U.S. Department of Health, Education and Welfare - National Air Pollution Control Administration Publication No. AP-67.

10. Control Techniques for Hydrocarbon and Organic Solvent Emissions from Stationary Sources - U.S. Department of Health, Education and Welfare, National Air Pollution Control Administration Publication No. AP-68.

11. Guide to Refinery Operating Costs - W. L. Nelson.

12. Petroleum Refinery Engineering - W. L. Nelson.

13. The Petroleum Handbook - Ed. Shell International Company, Ltd.

14. "Report on Full Scale Study of Inversion Breakup at Large Power Plants" - F. W. Thomas et al. - T.V.A. (March, 1970).

15. Environmental Reporter - November 10, 1972 (p. 804).

16. Student projects on coastal zone and offshore resources management - Report MITSG 72-13.

Chapter II.7
The Impact of a Gas Find on Regional Air Quality

II.7.1 Impact of gas find on SO_2 emissions

A Georges Bank discovery could affect regional air quality by changing the mix of fuels consumed by the region. An all-oil find is unlikely to have any effect as present (1975) regional standards involve an average maximum sulphur content of .8% with 16% of the consumption at .25% and another 56% of the consumption set at .5% or less. It is extremely unlikely that the crude found would result in fuel oils with sulphur contents this low without hydro-desulphurization. Thus, the impact of even a low-sulphur, all-oil find will almost certainly be focussed completely on the cost to the region of achieving the 1975 and later standards rather than on the levels of sulphur actually emitted. Further, as we have seen, even an extremely large find would satisfy New England's oil consumption for less than ten years, and most of the oil finds studied satisfied only a portion of the consumption even at peak production.

Gas is a somewhat different story. A gas find is unlikely to reduce emission of particulates, carbon monoxide, hydrocarbons, or nitrogen oxides because to a great extent the emissions are produced by cars, assuming of course gasoline-fired automobile engines continue in vogue. One area where a large gas discovery could have a significant impact is in emissions of sulphur oxides. Chapter I.2 estimates that the discovery of 1, 5, and 10 trillion cubic feet would be produced at a maximum rate of 68, 390, and 680 billion cubic feet per year respectively. Production will be maintained at these levels for five years and after that will fall at a rate of about 8.5% per year. Assuming that all this gas is put to fuel oil usage (space heating and utilities) and assuming 1975 regulation sulphur contents in the fuel oil and 2,000 grains of SO_2 per million cubic feet of gas, leads to the reduction in sulphur emissions shown in Tables II.7.1 and II.7.2. Table II.7.1 shows the results assuming a 4% annual growth in fuel oil consumption and II.7.2 the results for 2% growth in consumption. As can be seen, the percentage reduction due to a large gas find can be quite substantial for some time.

DESCRIPTION	YEAR 1	2	3	4	5	6	7	8	9	10
Fuel oil demand without nat. gas findings	76.35	79.40	82.58	85.88	89.31	92.89	96.60	100.4	104.4	108.6
Fuel oil demand with 1 trillion c.f. of gas findings	72.19	75.24	78.42	81.72	85.15	89.06	93.08	97.23	101.5	105.9
Fuel oil demand with 5 trillion c.f. of gas findings	55.55	58.60	61.78	65.08	68.51	73.75	79.00	84.27	89.58	94.96
Fuel oil demand with 10 trillion c.f. of gas findings	34.75	37.80	40.98	44.28	47.71	54.61	61.39	68.07	74.68	81.25
Total sulfur released without natural gas findings	0.605	0.629	0.654	0.681	0.708	0.736	0.766	0.796	0.828	0.861
Total sulfur released with 1 trillion c. f. of gas findings	0.572	0.596	0.621	0.648	0.675	0.706	0.738	0.771	0.804	0.840
Total sulfur released with 5 trillion c. f. of gas findings	0.440	0.464	0.490	0.516	0.534	0.584	0.626	0.668	0.710	0.753
Total sulfur released with 10 trillion c. f. of gas findings	0.275	0.299	0.325	0.351	0.378	0.433	0.487	0.540	0.592	0.644
Percent reduction for 1 trillion of c. f. gas findings	5.44	5.23	5.03	4.84	4.65	4.11	3.64	3.22	2.85	2.52
Percent reduction for 5 trillion of c. f. gas findings	27.22	26.17	25.17	24.20	23.27	20.58	18.21	16.11	14.25	12.60
Percent reduction for 10 trillion of c. f. gas findings	54.45	52.35	50.34	48.40	46.54	41.17	36.42	32.22	28.50	25.21

All values in billions of lb/year

Fuel oil demand includes residual and distillate oil

Average sulfur content of oil = 0.79 % (Average for 1975 regulations)

Average sulfur content of natural gas = 2,000 grains/10^6 s.c.f.

Energy content of oil = 4.7 million BTU/barrel

Energy content of gas = 1120 BTU/cf

Figure II.7.1 (4% annual growth in fuel oil consumption)

DESCRIPTION	YEAR 1	2	3	4	5	6	7	8	9	10
Fuel oil demand without nat. gas findings	76.35	77.87	79.43	81.02	82.64	84.29	85.98	87.70	89.45	91.24
Fuel oil demand with 1 trillion c.f. of gas findings	72.19	73.71	75.27	76.86	78.48	80.46	82.46	84.46	86.47	88.50
Fuel oil demand with 5 trillion c.f. of gas findings	55.55	57.07	58.63	60.22	61.84	65.16	68.37	71.50	74.55	77.53
Fuel oil demand with 10 trillion c.f. of gas findings	34.75	36.27	37.83	39.42	41.04	46.02	50.77	55.30	59.65	63.82
Total sulfur released without natural gas findings	0.605	0.617	0.629	0.642	0.655	0.668	0.681	0.695	0.709	0.723
Total sulfur released with 1 trillion c. f. of gas findings	0.572	0.584	0.596	0.609	0.622	0.638	0.653	0.669	0.685	0.701
Total sulfur released with 5 trillion c. f. of gas findings	0.440	0.452	0.465	0.477	0.490	0.516	0.542	0.567	0.591	0.614
Total sulfur released with 10 trillion c.f. of gas findings	0.275	0.287	0.300	0.312	0.325	0.365	0.402	0.438	0.473	0.506
Percent reduction for 1 trillion of c. f. gas findings	5.44	5.33	5.23	5.13	5.03	4.53	4.09	3.69	3.32	3.00
Percent reduction for 5 trillion of c. f. gas findings	27.22	26.69	26.16	25.65	25.15	22.68	20.46	18.45	16.64	15.01
Percent reduction for 10 trillion of c. f. gas findings	54.45	53.38	52.33	51.31	50.30	45.37	40.92	36.91	33.29	30.03

All values in billions of lb/year

Fuel oil demand includes residual and distillate oil

Average sulfur content of oil = 0.79 % (Average for 1975 regulations)

Average sulfur content of natural gas = 2,000 grains/10^6 s.c.f.

Figure II.7.2 (2% annual growth in fuel oil consumption)

Meade, R. H., after 1970, The Coastal Environment of New England, U.S. Geological Survey, Woods Hole, MA, printed and distributed by the New England River Basins Commission.

Neu, H. A., 1970, The Hydrodynamics of Chedabucto Bay and Its Influence on the "Arrow" Oil Disaster, Atlantic Oceanographic Laboratory, Bedford Institute, Dartmouth, Nova Scotia, Canada.

Phillips, O. M., 1969, The Dynamics of the Upper Ocean, Cambridge

Chapter II.3
Oil Spill Containment and Removal

II.3.1 Introduction

The two previous chapters have operated under the conservative assumption that no attempt is made to contain or clean up the spills described therein. This chapter summarizes the physics of oil spill collection and removal, develops a model for determining a preliminary model for costing booms and collection devices, and simulates these systems operating against a range of hypothetical spills in order to generate some insight into the effectiveness of these systems.

The analysis is complicated both by the large number of variables which one can manipulate in designing a spill collection and retrieval system (including boom length, strength and depth, collection device type and capacity, and time to deployment) and the large number of spills and wind and current conditions one can design to. Thus, our discussion will necessarily be somewhat general in nature. For the bulk of our quantitative analysis, we will rely heavily on Hoult (1969).